Some like it hot: maximising rugby sevens performance in the heat

by Mitchell Henderson

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of:
Distinguished Professor Aaron Coutts,
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University of Technology Sydney
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"I’ve never been certain whether the moral of the Icarus story should only be, as is generally accepted, ‘don’t try to fly too high,’ or whether it might also be thought of as ‘forget the wax and feathers, and do a better job on the wings."

Stanley Kubrick
on the tale from Greek mythology
of Icarus flying too close to the sun

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Mitchell Henderson, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Health at the University of Technology Sydney.

This thesis is wholly my work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

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Mitchell Henderson

11/02/2023

Date Submitted

PREFACE

This thesis for the degree of Doctor of Philosophy is in the format of published or submitted manuscripts and abides by the ‘Graduate Research Candidature Management, Thesis Preparation and Submission Procedures’ from the University of Technology, Sydney. All manuscripts included in this thesis are closely related in subject matter and form a cohesive research narrative.

This project was completed in partnership with Rugby Australia and the national women’s rugby sevens team. Based on the research design and data collected by the candidate, four manuscripts have been accepted for publication and one further has been submitted to a peer-reviewed journal. These papers are initially brought together by an introduction, which provides background information, and defines the research problem and the aim of each study. A literature review then follows to provide an overview of previous knowledge regarding thermophysiology and rugby sevens. The body of the research is presented in manuscript form (Chapter Three to Chapter Seven), in a logical sequence following the development of research ideas in this thesis (although before submission for publication, the systematic review presented in Chapter 3 was updated to include data from the study in Chapter 4 for completeness). Each manuscript outlines and discusses the individual methodology and the findings of each study separately. The General Discussion chapter provides an interpretation of the collective findings, makes some practical recommendations, and acknowledges the limitations of the series of investigations that comprise this thesis. Finally, a Summary and Recommendations chapter presents the conclusions from each project and directions for future research to build on the findings of this thesis are suggested. The UTS Harvard reference style has been used throughout the document and the reference list is at the end of the thesis.

ACKNOWLEDGEMENTS

I'm extremely grateful to the players and staff at the Aussie 7's for their support during this project. Some of my biggest professional learnings and best professional memories are from my time within the program. I will always look back on it fondly.

I'd like to thank Franco Impellizzeri, Clementine Grandou, Bryna Chrismas, Chris Stevens, and Andrew Novak who have all contributed directly to this thesis and my development during this project. It's been a pleasure collaborating and getting to know you all personally and professionally.

I'm deeply indebted to my supervisory team: Aaron Coutts, Lee Taylor, and Job Fransen. I attribute much of my development as a researcher and practitioner to the knowledge and experiences I've been afforded as a result of being your student. I want to thank you all for your guidance, patience, and kindness. It's been a privilege and I'll be forever grateful.

I'm fortunate to have always been supported unconditionally by my family with every endeavour I've chosen in life. For this I want to express my deepest appreciation. I do not take it for granted.

And finally, to Emma; my soon-to-be wife. Thank you for being by my side through anything and everything.

PUBLICATIONS BY THE CANDIDATE RELEVANT TO THE THESIS

Henderson, M.J., Chrismas, B.C.R., Stevens, C.J., Coutts, A.J. & Taylor, L. (2020). Core temperature changes during an elite female rugby sevens tournament. *International Journal of Sports Physiology and Performance*, 15(4): 571 – 580.

Henderson, M.J., Chrismas, B.C.R., Stevens, C.J., Novak, A.R., Fransen, J., Coutts, A.J. & Taylor, L. (2020). Additional clothing increases heat-load in elite female rugby sevens players. *International Journal of Sports Physiology and Performance*, 16(10): 1424 – 1431.

Henderson, M.J., Chrismas, B.C.R., Stevens, C.J., Fransen, J., Coutts, A.J. & Taylor, L. (2021). Limiting the rise in heat-load with an ice-vest during elite female rugby sevens warm-ups. *International Journal of Sports Physiology and Performance*, 16(11): 1684 – 1691.

Henderson, M.J., Chrismas, B.C.R., Fransen, J., Coutts, A.J. & Taylor, L. (2022). Responses to a 5-day sport-specific heat acclimatization camp in elite female rugby sevens athletes. *International Journal of Sports Physiology and Performance*, 17(6): 969 – 978.

Henderson, M.J., Grandou, C., Chrismas, B.C.R., Coutts, A.J., Impellizzeri, F.M. & Taylor, L. (2023). Core body temperature in intermittent sports: A systematic review. *Sports Medicine*, In press.

ABSTRACT

When athletes perform or train in thermally challenging conditions, they are subject to added physiological strain. The physical demands of rugby sevens and the competition environment form a considerable thermo-physiological challenge for athletes that may threaten athlete health and performance. At present, whilst there is a well-developed understanding of the consequences of exercise in the heat for endurance sports, relatively little is known on its effects on sports requiring an intense intermittent activity profile, such as rugby sevens. This thesis contains five studies that aimed to provide evidence-informed, feasible solutions that assist high-level female rugby sevens athletes that compete in thermally challenging environments. The first two studies described levels of hyperthermia experienced in-competition in (1) a range of intermittent sports (study one); and (2) within elite women's rugby sevens (study two). The findings showed almost 90% of the included studies reported some degree of hyperthermia (including women's rugby sevens). Studies three and four provided proof of concept for feasible approaches to heat acclimation (additional clothing; study three) and pre-cooling interventions (phase-change vest; study four) that could help elite female rugby sevens athletes mitigate thermal strain in situ. The results of study three showed that training in hot conditions provides comparable core body temperatures to the matches in temperate conditions observed in study two, and that additional clothing worn during training can be a viable and effective method to increase the heat strain experienced. Study four found wearing phase change cooling vests before, and during the warm-up limited the rise in core body temperature before a match, but only in hot conditions. Study five described the responses to a real five-day heat acclimatisation program for rugby sevens where training content remained rugby specific. Beneficial cardiovascular adaptations were found without expensive facilities/equipment or changing training content. Changes in resting core temperature, sweat rate, and thermal effort/perceptions likely required a greater thermal impulse. Collectively, these findings support the development of integrated training plans aimed at maximising physical capacity in rugby sevens through heat tolerance adaptations. The findings from the series of studies in this thesis has contributed to a narrowing of the gap between research and practice and supported athletes preparing for the Olympic Games.

STATEMENT OF CONTRIBUTION BY OTHERS

This thesis details original research conducted by the candidate at Rugby Australia while enrolled in the Faculty of Health at the University of Technology Sydney. The thesis includes research articles of which I am the lead author and was primarily responsible for the conception and design of the research, ethical approval to conduct the research, data collection, analysis and interpretation, manuscript preparation, and correspondence with journals.

Where explicitly acknowledged in each experimental chapter, several individuals have contributed to the research presented in this thesis.

- Dr Lee Taylor: Study design, data interpretation and manuscript review
- Dist. Prof. Aaron J. Coutts: Study design and manuscript review
- Dr Job Fransen: Data analysis and interpretation, and manuscript review
- Prof. Franco Impellizzeri Study design, data interpretation, manuscript review
- Clementine Grandou Data collection and manuscript review
- Dr Bryna C.R. Chrismas: Data collection and manuscript review
- Dr Christopher J. Stevens Manuscript review
- Dr Andrew R. Novak: Data analysis and manuscript review

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CONTENTS

LIST OF ABBREVIATIONS

AC	additional clothing
AFL	Australian Rules Football
AU	arbitrary units
Ave Acc/Dec	average acceleration/deceleration
BL	baseline
BLa	blood lactate
CI	confidence interval
CON	control
CWI	cold water immersion
CV	coefficient of variation
EHI	exertional heat illness
ES	effect size
FIFA	International Federation of Association Football
GPS	Global positioning systems
HA	heat acclimation / acclimatisation
HR	heart rate
HRex	exercising heart rate
HSR	high speed running
HWI	hot water immersion
IAAF	International Association of Athletics Federations
ICC	Intraclass correlation coefficient
IQR	Interquartile range
LBM	lean body mass
LMM	linear mixed model
LTHA	long term heat acclimation / acclimatisation
m	metres
MAP	mean arterial pressure

max	maximum
min	minimum
MTHA	medium term heat acclimation / acclimatisation
NRCT	non-randomised controlled trial
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCT	randomised controlled trial
RH	relative humidity
RPE	rating of perceived exertion
s	seconds
SE	standard error
SF	skinfold
STHA	short term heat acclimation / acclimatisation
T_c	core body temperature
TC	Thermal comfort
T_{sk}	skin temperature
TS	Thermal sensation
VHSR	very high-speed running
VO_2max	maximal volume of oxygen consumption
WBGT	wet bulb globe temperature
WRWSS	World Rugby Womens Sevens Series
WU	warm-up

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CHAPTER 1 | INTRODUCTION

BACKGROUND

Rugby sevens is a shorter-duration variant of rugby union where each team competes with only seven athletes on the field on a full-sized rugby pitch. Conceived by two butchers and local athletes from Melrose, Scotland in 1883 as a fund-raising event for their local rugby club, rugby sevens popularity spread throughout the Commonwealth in the late 19th and early 20th centuries. The quadrennial Rugby World Cup Sevens was launched in 1993 for men, where the Melrose Cup is contested, and in 2009 for women. Regular annual international competition began with the men's World Rugby Sevens Series in 1999 and World Rugby Women's Sevens Series (WRWSS) in 2012. In 2016, rugby sevens was contested at the Summer Olympic Games for the first time. Currently, international competition occurs in tournaments consisting of five or six matches over two to three days. The greater relative field space (area per player) and shorter match duration allow for higher average running intensities [109.6 $m \cdot min^{-1}$ for men and 102.2 $m \cdot min^{-1}$ for women (Ball, Halaki & Orr 2019)] when compared to rugby union [69.7 $m \cdot min^{-1}$ for men (Cunningham et al. 2016) and 68.5 $m \cdot min^{-1}$ for women (Suarez-Arrones et al. 2014)] at the international level. Athletes require a balance of well-developed endurance and neuromuscular capacities to support the high-intensity physical demands of rugby sevens. This high-intensity work generates significant metabolic heat (Cheung 2010). When this heat is not adequately dissipated, thermal strain is generated; a collective term encompassing various factors such as core body temperature (T_c) and skin temperature (T_{sk}). This is often exacerbated by local environmental conditions as international rugby sevens tournaments are commonly scheduled in spring and summer months to minimise clashing with the traditional winter rugby union seasons and in locations with perennially hot and humid climates (e.g., Dubai, Singapore, Hong Kong) (Fenemor et al. 2022). Combined, the physical demands of the sport and the competition environment provide a considerable thermo-physiological challenge for athletes and practitioners to manage in pursuit of health and high performance.

When athletes exercise in thermally challenging conditions, they are subject to added physiological strain when compared to the same work in temperate conditions (Ely et al. 2007; Guy et al. 2015; McArdle 1981; Tyler et al. 2016). The resulting excess heat gain can develop into hyperthermia with associated reductions in physical and cognitive performance (Nybo

2008). Endurance exercise performance is particularly compromised due to competition between central and peripheral oxygen demands in thermally challenging environments (Nybo, Rasmussen & Sawka 2014). In comparison to endurance events, the effects of thermal strain on performance in team sports are less understood. High-level team sport athletes consistently generate T_c above 39°C during competition regardless of the ambient environmental conditions (Nybo et al. 2013). This magnitude of thermal strain has been shown to impair repeated-sprint (< 60 s between efforts) (Drust et al. 2005; Girard, Brocherie & Bishop 2015), intermittent-sprint (60-300 s between efforts) (Sunderland & Nevill 2005), and neuromuscular performances (Morrison, Sleivert & Cheung 2004; Nybo & Nielsen 2001). Maximising the capacity for rugby sevens athletes to express these qualities during a match is an important component of the physical construct of the sport. Currently, most of the available evidence is based on findings from endurance athletes performed in laboratories. Whilst controlled settings such as these enable studies to be conducted with a higher level of evidence, applied research with direct application and translation is necessary to determine the generalisability of the findings to diverse and dynamic environments. Laboratory findings such as these are theoretically important, but the transferability to practice is less clear due to contextual factors such as scheduling, training specificity concerns, financial cost, large athlete numbers, and access to equipment or facilities. Practice-facing research conducted with an applied lens is required to support rugby sevens athletes and practitioners that evaluate the ecological validity of the laboratory findings in the complex and constrained environment of training and competition in international rugby sevens.

There is also limited research examining the effects of hyperthermia and heat training interventions on female athletes (Giersch et al. 2020; Hutchins et al. 2021). This disparity is observed across sports science research as a whole with only 34% of participants being female (Cowley et al. 2021). The limited available evidence suggests that compared to men, women require a stronger heat training dose (e.g., longer duration, greater heat stress, more sessions) to achieve comparable adaptation to heat stress than males (Wickham, Wallace & Cheung 2020). This may be explained by sex-based differences in anthropometry, training status, or menstrual cycle-related variations in T_c (Wickham, Wallace & Cheung 2020). As a result, the current evidence supporting best practice preparation for team sport athletes competing in hot and humid conditions may not be applicable for female athletes.

Finally, evidence-based practice in sports science and medicine requires the integration of individual clinical expertise (practise-based evidence) with the best available evidence from research (research-based evidence) to inform decision-making (Coutts 2017; Sackett et al. 1996). Without professional expertise (that accounts for athlete preferences and values), practice risks becoming tyrannised by the requirement for high levels of evidence from research. Conversely, without the best available research evidence, practices may be unfounded. An adaptation of this general philosophy has been developed for use in sports settings to extend the core tenets of evidence-based practice to also include consideration of feasibility in practice (Ardern et al. 2019). Best research evidence does not always translate to the constrained training and competition environments that athletes and practitioners are often required to operate within. The topic of heat acclimation is a good example of an area of research with a gap between research-based and practice-based evidence (Casadio et al. 2017). Guidelines for athletes are well-established, but clinical expertise is still lacking in applying them effectively within the constraints of the multiple competing demands that are common for athletes (e.g., technical/tactical training, travel, and media). Evidence that accounts for the diverse feasibility challenges specific to international rugby sevens is required to support evidence-based practice. This research would aim to test the effectiveness ‘in the wild’ of interventions developed in more controlled settings, providing valuable feedback for the design of future laboratory studies that possess higher ecological validity. Building upon mechanistic studies with applied research such as this bridges the gap between research and practice and ultimately promotes a meaningful and effective impact on practice and performance (Slattery, Crowcroft & Coutts 2021).

RESEARCH PROBLEM

Rugby sevens is the variant of rugby with the highest running intensity and international multi-day tournaments are often hosted in locations with hot and humid climates. A considerable body of research supports impaired athletic performance when thermal strain is severe. Most of the available sports thermophysiology evidence is based on data collected from male endurance athletes. This limits the feasibility of the methods and generalisability of the findings for (1) team sport athletes with more intermittent physical demands and (2) female athletes with endocrinological and anthropometric differences from males. Even less evidence is available in female athletes at the elite level where small changes are often meaningful and implications on performance are of the greatest consequence. To provide solutions to this research problem that transfer to practice, study designs from the field with relatively high ecological validity are required to build upon the existing theoretical and mechanistic research completed in more controlled settings. This thesis, therefore, aims to provide practical, evidence-based approaches to prepare for the thermal challenges of rugby sevens using data collected from elite female athletes.

STUDY OBJECTIVES

A series of applied research studies were conducted with the collective aims of (1) determining the magnitude of heat strain induced by competing in intermittent-style sport, (2) characterising the thermal challenges of elite rugby sevens in female athletes, (3) determining the effects of practical and cost-effective strategies for team sport athletes to prepare for performance in hot and humid conditions, and (4) assessing the impact of a fully integrated heat acclimation training block on physiological performance indicators.

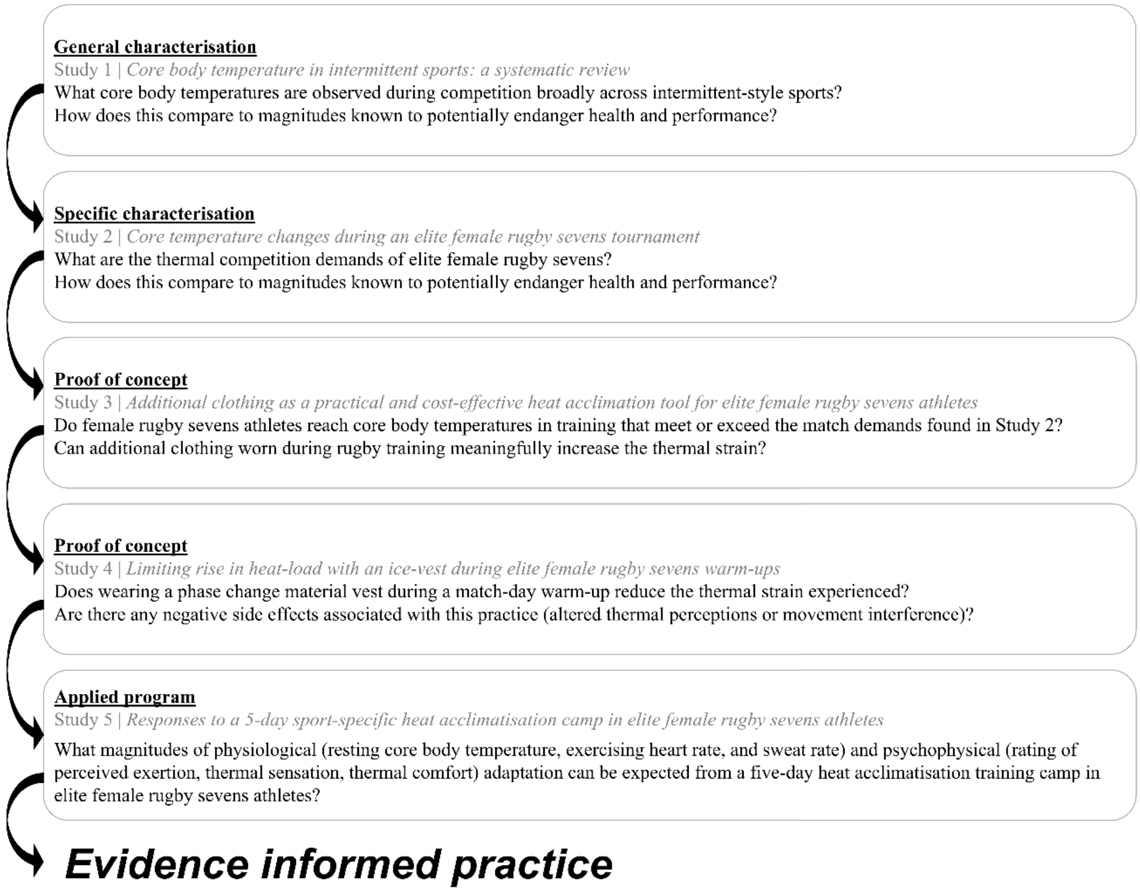


Figure 1.1 Sequence linking the studies undertaken in this thesis.

STUDY ONE: CORE BODY TEMPERATURE IN INTERMITTENT SPORTS: A SYSTEMATIC REVIEW

AIM

To synthesise and characterise the available core temperature data collected in competition from intermittent sport athletes.

SIGNIFICANCE

Hyperthermia (and associated health and performance implications) can be a significant problem for athletes and teams involved in intermittent sports. Quantifying the peak T_c from a range of intermittent sports would enhance the knowledge of their thermal demands and eventually inform decisions regarding the need for training or match-day interventions to minimise thermally mediated harm and/or performance reductions.

STUDY TWO: CORE TEMPERATURE CHANGES DURING AN ELITE FEMALE RUGBY SEVENS TOURNAMENT

AIM

To characterise the T_c responses of elite female rugby sevens athletes within and between matches of a WRWSS tournament day and determine the efficacy of post-game cold water immersion protocols.

SIGNIFICANCE

High T_c (of a magnitude associated with performance impairment) have been observed during temperate/warm matches in elite male rugby sevens athletes. There currently is no published T_c data in elite female rugby sevens athletes and thus it is unknown whether hyperthermia during competition threatens the performance and health of competing female athletes. Cold water immersion is a commonly used recovery modality following WRWSS matches, but there is no published data on the efficacy of this intervention in alleviating high T_c.

STUDY THREE: ADDITIONAL CLOTHING INCREASES HEAT-LOAD IN ELITE FEMALE RUGBY SEVENS PLAYERS

AIM

To (1) determine how female rugby sevens athletes' T_c in training relate to the match data collected in Study 2, and (2) investigate whether additional clothing worn during a hot training session meaningfully increases the heat load experienced.

SIGNIFICANCE

Whether routine training for rugby sevens generates the necessary thermal load to prepare athletes for the demands of matches has not been established. Any disparity in this relationship has ramifications for physical preparation strategies.

Financial and time constraints within team sport preparations often limit the interventions that can be used to facilitate adaptations that assist athletes to cope with competing in the heat. Rugby sevens training with additional clothing may provide a practically compatible and cheap tool to increase heat strain and offset any potential thermal mismatch between training and matches (without impairing training specificity).

STUDY FOUR: LIMITING RISE IN HEAT-LOAD WITH AN ICE-VEST DURING ELITE FEMALE RUGBY SEVENS WARM-UPS

AIM

To determine the effect of wearing a phase-change cooling vest within elite female rugby sevens athletes during (1) a simulated match day warm-up in hot conditions before a training session; and (2) a pre-match warm-up during a tournament in cool conditions.

SIGNIFICANCE

Pre-cooling using a phase-change ice vest has demonstrated favourable alterations in physiological and perceptual warm-up responses in elite male rugby sevens athletes. No T_c data collected during a pre-cooling intervention in female rugby sevens athletes currently exists despite potentially being of greater concern (and more effective) due to between-sex differences in athlete anthropometrics and reproductive physiology/endocrinology influencing thermoregulation.

STUDY FIVE: RESPONSES TO A 5-DAY SPORT-SPECIFIC HEAT ACCLIMATISATION CAMP IN ELITE FEMALE RUGBY SEVENS ATHLETES

AIM

Describe the physiological (resting T_c, exercising heart rate, sweat rate) and psychophysical (rating of perceived exertion, thermal sensation, thermal comfort) responses to a short-term heat acclimatisation training camp in elite female rugby sevens athletes.

SIGNIFICANCE

Pragmatism is required when planning and implementing interventions aimed at procuring adaptations to heat within the constraints of team sports preparation. Shorter heat acclimation/acclimatisation protocols that are viable for a large group, whilst retaining some benefits associated with more comprehensive protocols, will be of value to practitioners working in elite team sport contexts.

Research regarding heat training adaptations has mostly focused on males, limiting applicability to female athletes. This limited available evidence suggests females require a stronger heat dose (e.g., longer exposure, greater heat stress, more sessions) to achieve comparable adaptation to males. Practitioners supporting female athletes preparing for thermally-challenging events will benefit from a more robust understanding of the minimal effective dose to achieve a given physiological response.

CHAPTER 2 | LITERATURE REVIEW

Heat and temperature are two of the most central foundations of all biological systems; impacting the successful development, maturation, and functioning of even the most basic units of life (Leuenberger et al. 2017). In human physiology, changes of several degrees in resting T_c away from a narrow physiological homeostatic resting set-point (e.g., 36 – 37.5°C) can quickly become fatal (Charkoudian 2010; Lim, Byrne & Lee 2008). The impact of heat on performance in athletic and occupational populations continues to be investigated. The combination of prolonged endurance or relatively short but maximal effort exercise in hot/humid conditions (exercise heat-stress) decrement performance whilst increasing exertional heat illness (EHI) risk (Guy et al. 2015); EHI can be fatal during occupations pursuits (Kark et al. 1996), and recreational (Binkley et al. 2002) and professional sport (Casa et al. 2005).

The Tokyo 2020/1 Olympic Games and 2019 International Associations of Athletics Federations (IAAF) World Championships in Doha have intensified this interest, as policy makers seek to ensure the safety of spectators, athletes, and support staff; and athletes and practitioners seek to limit heat-mediated performance decrements. One example of an athletic cohort that commonly encounters thermally-challenging competition conditions are elite rugby sevens players, who contest tournaments in the southern and northern hemispheres resulting in variable environmental match-day conditions (Henderson et al. 2020). Rugby sevens teams can travel from their domestic winter months to compete in summer months elsewhere, often facing extremes of heat and/or humidity without a fully heat-acclimatised or acclimated phenotype. Furthermore, rugby sevens will be contested outdoors at the Tokyo 2020/1 Olympics – likely the hottest and most humid modern Olympics to date (Gerrett et al. 2019; Kakamu et al. 2017; Kashimura, Minami & Hoshi 2016; Kissling, Akerman & Cotter 2020).

This review will examine the literature relating to the impact of human thermal physiology on athletic performance for elite rugby sevens athletes and practitioners. Proposed methods to maximise performance in the heat will be discussed, as will the potential barriers to current practice and challenges in translating research into evidence-informed athletic preparation.

RUGBY SEVENS

The World Rugby Women's Sevens Series (WRWSS) is the premier women's international rugby sevens series/competition, with 8 tournaments per season as of the 2019/2020 season. Tournaments are competed over 2 – 3-day periods, with up to 3 matches per day and ~3 hours between matches. Teams accumulate points based on their finishing position in each of the tournaments that comprise the World Series. The team with the highest accumulated points total following the completion of all tournaments is crowned the series champion (Henderson et al. 2018), with the top 4 teams also gaining direct qualification to the Olympics during qualifying years.

Rugby sevens is a field-based team sport, a derivative of 15-a-side rugby union requiring a unique interplay of well-developed athletic capacities (Ross, Gill & Cronin 2015). Teams of seven players (and five reserves) aim to manipulate space and advance the ball across the opponent's try-line to score points. The game is played on the same field dimensions as rugby union (100 x 70 m) but contested over seven-minute halves typified by frequent bouts of high-intensity running, rapid accelerations/decelerations and collisions, varied by playing position (Henderson et al. 2018). WRWSS match-play has reported average speeds of 86 ± 4 $m \cdot min^{-1}$ with $11 \pm 3\%$ performed above 5 $m \cdot s^{-1}$ (Clarke, Anson & Pyne 2017). In addition to the match play demands, WRWSS participation involves challenging long-haul travel schedules as tournaments are played across multiple continents (Asia, Africa, North America, Europe, and Oceania). This introduces uniquely regular demands relative to jet-lag and travel fatigue-related performance impairments, compromised sleep and recovery, and subsequent heightened illness risk (Fowler, Duffield & Vaile 2015; Lee & Galvez 2012; Mitchell, Pumpa & Pyne 2017); this regularity is not commonly present in the majority of other elite field-based team sport.

These travels demands expose WRWSS athletes to variable match-day conditions within and across seasons (Taylor, Thornton, et al. 2019). Teams can travel from their domestic winter months to compete in summer months elsewhere, often facing extremes of heat and/or humidity without the protection and benefit of a fully heat-acclimatised or acclimated phenotype. Previous research has characterised the T_c responses of elite male rugby sevens players across two World Rugby Sevens Series tournaments (Taylor, Thornton, et al. 2019). Considering the high T_c observed from temperate/warm match-play in males (Taylor, Thornton, et al. 2019) capable of reducing physical performance (Girard, Brocherie & Bishop 2015), other hotter tournaments of the WRWSS or major sporting events such as the Olympic or Commonwealth Games may challenge practitioners to manage player body temperatures for optimal performance. This is particularly significant for females due to their generally lower sweat responses (Gagnon, Crandall & Kenny 2013; Gagnon & Kenny 2011) and aerobic capacity (Yanovich, Ketko & Charkoudian 2020) in comparison to males, which can result in accelerated rates of heat gain. Additionally, thermal preparation may also be of greater importance due to changes in body temperature, blood pressure, and exercise performance across the menstrual cycle (Charkoudian et al. 2017; Janse et al. 2012).

Currently, no published data exist on rugby sevens players of any level investigating the efficacy of heat training methods in developing beneficial physiological adaptations for heat tolerance. Further, T_c responses to competition demands have yet to be established for elite females [as has been done for elite males (Taylor, Thornton, et al. 2019)], despite the biological differences limiting the generalisability of male findings. Finally, despite over fifty years of heat acclimation (HA) and cooling research (Tyler et al. 2016; Tyler, Sunderland & Cheung 2015), there is a paucity of female team sport-specific data to evidence-base practice upon, with many contemporary suggestions based on endurance paradigms lacking external validity to elite female team sport players (Bongers, Hopman & Eijsvogels 2017; Casadio et al. 2017; Mujika et al. 2018).

HUMAN THERMAL PHYSIOLOGY

Heat transfer in humans is a dynamic integrative process involving numerous physiological and psychological systems operating in a negative feedback loop to maintain homeostasis. The process of human heat transfer is derived from the First Law of Thermodynamics and is summarised by the heat balance equation (Cheung 2010) (see Figure 2.1):

$$S = M \pm W - E \pm C \pm K \pm R$$

Figure 2.1 Heat balance equation (Cheung 2010): S: storage of body heat, M: metabolic heat production, W: work, E: evaporative heat transfer, C: convective heat transfer, K: conductive heat transfer, R: radiant heat transfer.

This model can be simply described as a body's heat storage (positive [i.e., heat gain], neutral [i.e., thermal balance], or negative [i.e., heat loss]) is due to:

1. metabolic heat production (M; always positive),
2. mechanical work (W; can be either positive or negative),
3. and the four heat transfer pathways (which can all be either positive or negative):
    a. evaporative (E): evaporation of water (usually sweat) from the body
    b. convective (C): transfer of heat between the body and a fluid or gas
    c. conductive (K): transfer that occurs between the body and a solid surface
    d. radiant (R): transfer of heat via electromagnetic waves

This equation is measured in watts (W), a measure of heat flow, although commonly reported relative to surface area (W/m^2) or body mass (W/kg).

Homeostatic body temperature regulation mechanisms/responses, against both heat-loss and heat-gain, are dichotomised into autonomic (involuntary) and behavioural (voluntary) categories (Périard & Racinais 2019). Specific responses to external stimuli are executed to modulate body heat storage differentially whether stimuli are hot or cold (see Figure 2.2).

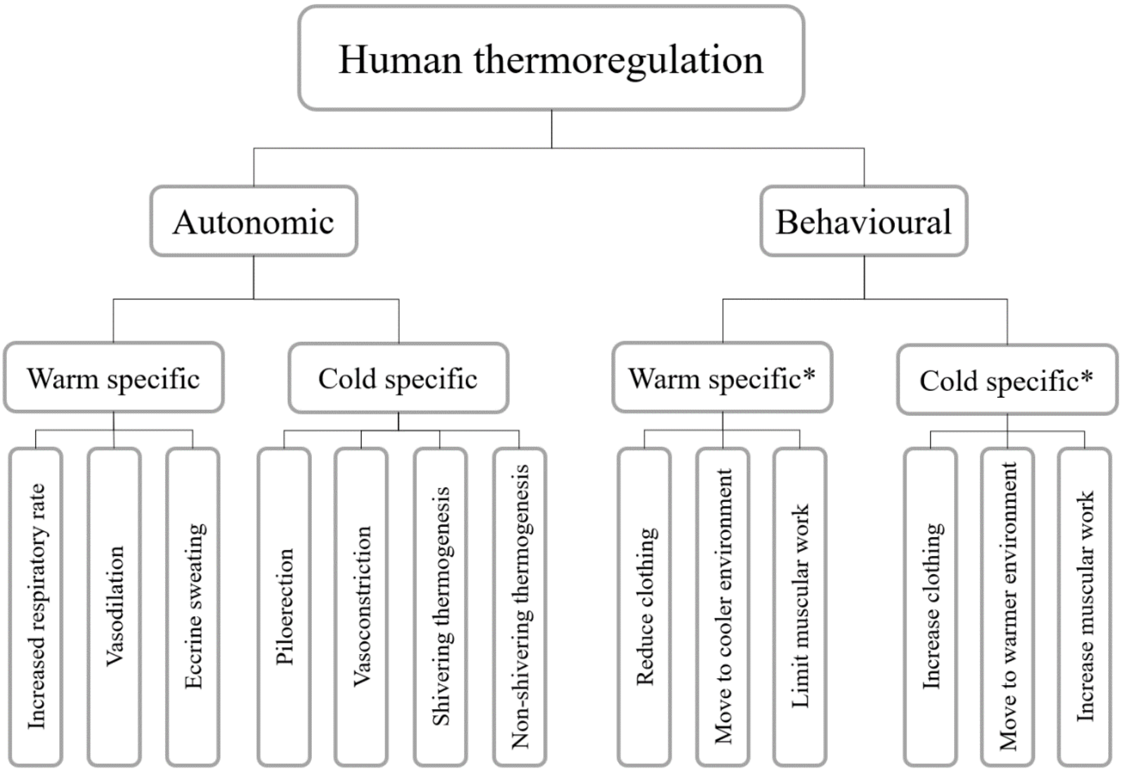


Figure 2.2 Conceptual model of human thermoregulation system**.** The asterisks denote that the provided responses are some examples of the multitude of behavioural response options. Taken from Périard & Racinais 2019.

EFFECT OF HEAT ON PERFORMANCE

When athletes perform or train in thermally challenging conditions, they are subject to added physiological strain when compared to the same work in temperate conditions (Ely et al. 2007; Guy et al. 2015; McArdle 1981; Tyler et al. 2016). Aerobic exercise capacity is particularly compromised during acute heat exposure due to thermoregulatory mediated cardiovascular adjustments (known as cardiovascular drift, see Figure 2.3), hyperthermia-induced skeletal muscle metabolism alterations, and central nervous system perturbations (see Figure 2.4) (Nybo, Rasmussen & Sawka 2014). In comparison to endurance events, the effects of heat on performance in team sports is less understood. This is likely due to the complexity of team sport movement patterns, and constraints in practice (e.g., large athlete numbers) and equipment (e.g., access to climate-controlled spaces) that are available to athletes and support staff.

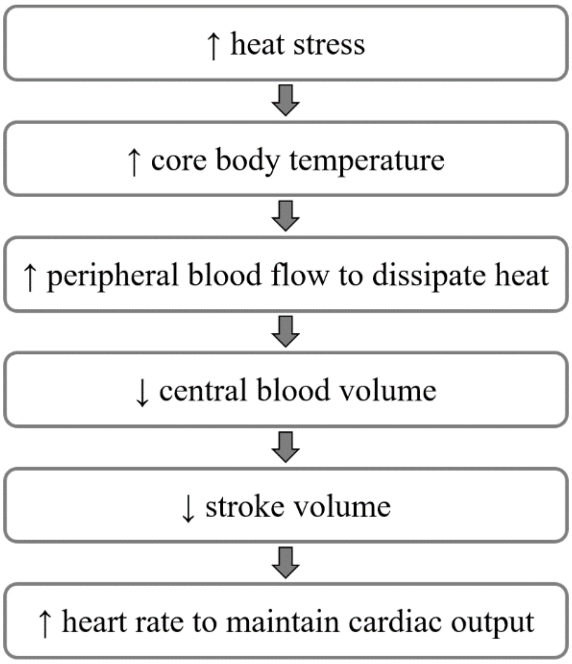


Figure 2.3 Cardiovascular drift. Taken from Tyler 2019.

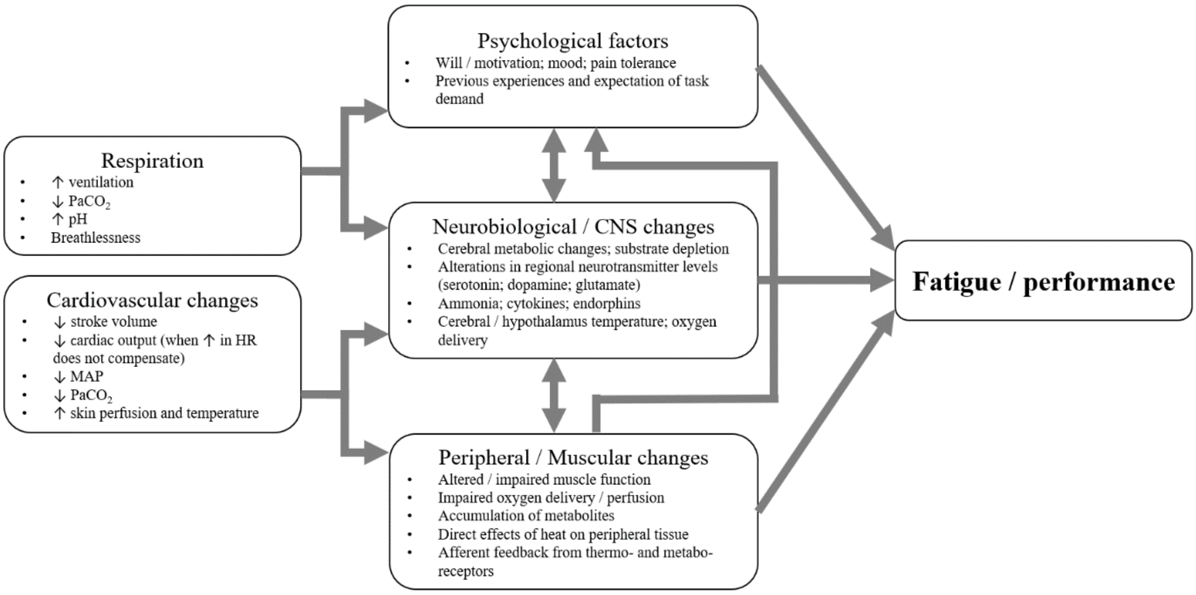


Figure 2.4 Integrative model with the potential cardiovascular, respiratory, central nervous system, and peripheral factors summarised that may influence fatigue during prolonged exercise in the heat. $PaCO_2$: partial pressure of carbon dioxide; pH: potential of Hydrogen; HR: heart rate; MAP: mean arterial pressure. Modified from Nybo, Rasmussen & Sawka (2014).

Research suggests that when T_c exceeds 39°C (i.e., hyperthermia) during team-sport type competition, central nervous system function (Girard, Brocherie & Bishop 2015), repeat sprint ability (<60 s between efforts) (Drust et al. 2005; Girard, Brocherie & Bishop 2015), and intermittent sprint performance (60-300 s between efforts) is compromised (Sunderland & Nevill 2005). Elite team sport athletes consistently generate T_c above 39°C during competition regardless of the ambient environmental conditions (Nybo et al. 2013; Périard et al. 2014a), with Australian Football League (AFL) players tolerating T_c up to 40.5°C when competing in hot conditions (Aughey, Goodman & McKenna 2014). Whilst it is well known that a T_c of >39°C decrements intermittent sprint performance (Girard, Brocherie & Bishop 2015), many of these assumptions are made on simulated sport (Aldous et al. 2018) or experimental match play (Mohr et al. 2012) lacking external validity. These findings are relied upon due to limited match play data, limited data from elite athletes, and limited data from females. Taken collectively, the combined effects of hot and humid competition conditions on health and performance endanger the otherwise potentially successful outcome of the training program.

Logistical constraints have limited the potential for more robust team sport-specific thermoregulation research when compared to endurance sports. These include (1) appropriate technology for T_c and T_{sk} measurement during competition and training; (2) sufficient sample sizes; and (3) semi-chaotic team sport match play characteristics. Because of the large variability in physical performance resulting from the contextual factors that influence game demands (Henderson et al. 2019), detecting meaningful inferences from interventions is challenging. This is due to the requirement for practically unrealistic sample sizes (e.g., elite soccer sample required is 80 players) to overcome the poor reliability observed in physical match performance measures such as high-speed running (Aldous et al. 2018; Gregson et al. 2010). Whilst tympanic temperature (unreliable) has been recorded in professional men's rugby league competition (Meir, Brooks & Shield 2003), and T_c has been reported in elite men's rugby sevens (Taylor, Thornton, et al. 2019), female-specific data is currently lacking in the rugby codes and sports science in general (Cowley et al. 2021). Practitioners working in women's sports require such data to justify the development of best-practise interventions to maximise the welfare and performance of female athletes in hot and humid conditions.

MAXIMISING TEAM SPORTS PERFORMANCE IN THE HEAT

Practitioners seeking to mitigate the performance-compromising effects of heat stress have several evidence-supported methods to consider for integration within their practice. These protocols can be broadly classified by their time course of action (see Figure 2.5).

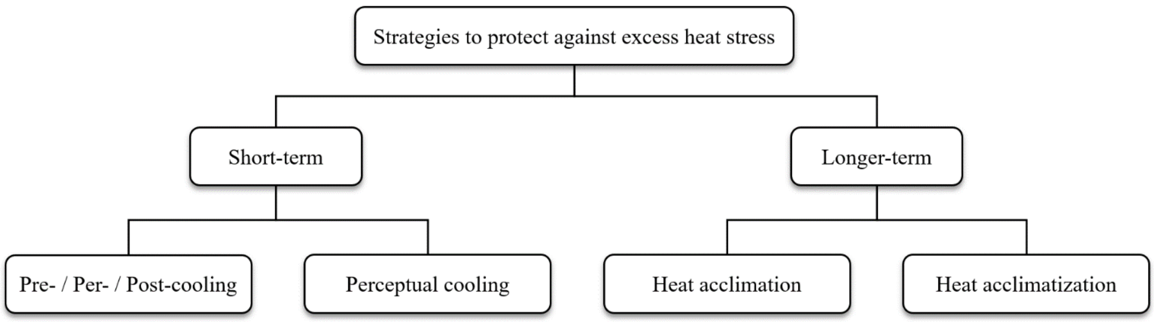


Figure 2.5 Summary of the common strategies used to mitigate heat-related performance impairments.

COOLING

Short-term strategies to minimise excess heat stress are aimed at lowering the starting level of physiological (e.g., T_c or T_{sk}) and perceptual [e.g., thermal comfort (TC) and thermal sensation (TS)] thermal strain, creating a larger heat storing capacity so performance may be maintained for longer in hot conditions (Ross et al. 2013; Tyler 2019). These methods involve pre-cooling (i.e., before exercise) and per-cooling (i.e., during exercise), protocols; and were employed by 52% of competing athletes in preparation for the 2015 International Association of Athletics Federations (IAAF) World Championships in anticipation of hot competition conditions (Périard et al. 2017). In sports with multiple bouts within a day (such as rugby sevens), post-exercise cooling methods such as cold-water immersion (CWI) are also a viable option for practitioners seeking to offset the heat gained from the prior bout, allowing a lower starting level of thermal strain in future bouts (Ihsan, Watson & Abbiss 2016). Despite the popularity of cooling methods within endurance contexts, unclear or equivocal results in team sports and implementation feasibility concerns in constrained environments such as team sports has led to lesser adoption (Bongers, Hopman & Eijsvogels 2017).

Multiple evidence-based modalities are available to practitioners seeking performance benefits of pre- and/or per-cooling such as CWI, cold beverage ingestion, ice-vest, head and neck cooling garments, and fan cooling (Bongers, Hopman & Eijsvogels 2017; Périard et al. 2017) but the research supporting these methods have mostly been conducted in endurance athletes. The optimal pre-cooling strategy to improve performance is reported to vary depending on the sport and environmental conditions (Bongers, Hopman & Eijsvogels 2017), suggesting that the application of endurance-based findings may not directly apply in team sports. This is demonstrated by the apparent loss of beneficial pre-cooling effects on repeat-sprint performance when an athlete is partially heat acclimated as is common in team sports (Brade, Dawson & Wallman 2012; Brade, Dawson & Wallman 2013). Greater pre-cooling performance benefits have been observed as the duration of sport increases and ambient temperature rises (Wegmann et al. 2012) with “mixed methods” cooling (i.e., combining a variety of pre-cooling approaches) suggested be the most effective strategy (Figure 2.6A and 2.6C) (Bongers, Hopman & Eijsvogels 2017). Per-cooling aims to address the diminishing effects of pre-cooling during exercise (Arngrímsson et al. 2004; Booth, Marino & Ward 1997; Duffield et al. 2010; Hasegawa et al. 2006; Kay, Taaffe & Marino 1999; Quod et al. 2008), extending the period of lessened thermal strain. Per-cooling options include facial wind or water spray, menthol, and cooling vests/packs (Figure 2.6B and 2.6D) (Tyler 2019) and are subject to the same external validity concerns when applied to team sports as previously discussed. Attempts have been made to maximise cooling benefits by combining pre- and per-cooling, but current reports suggest similar performance enhancements to using either method alone (Bongers et al. 2014; Bongers, Hopman & Eijsvogels 2017).

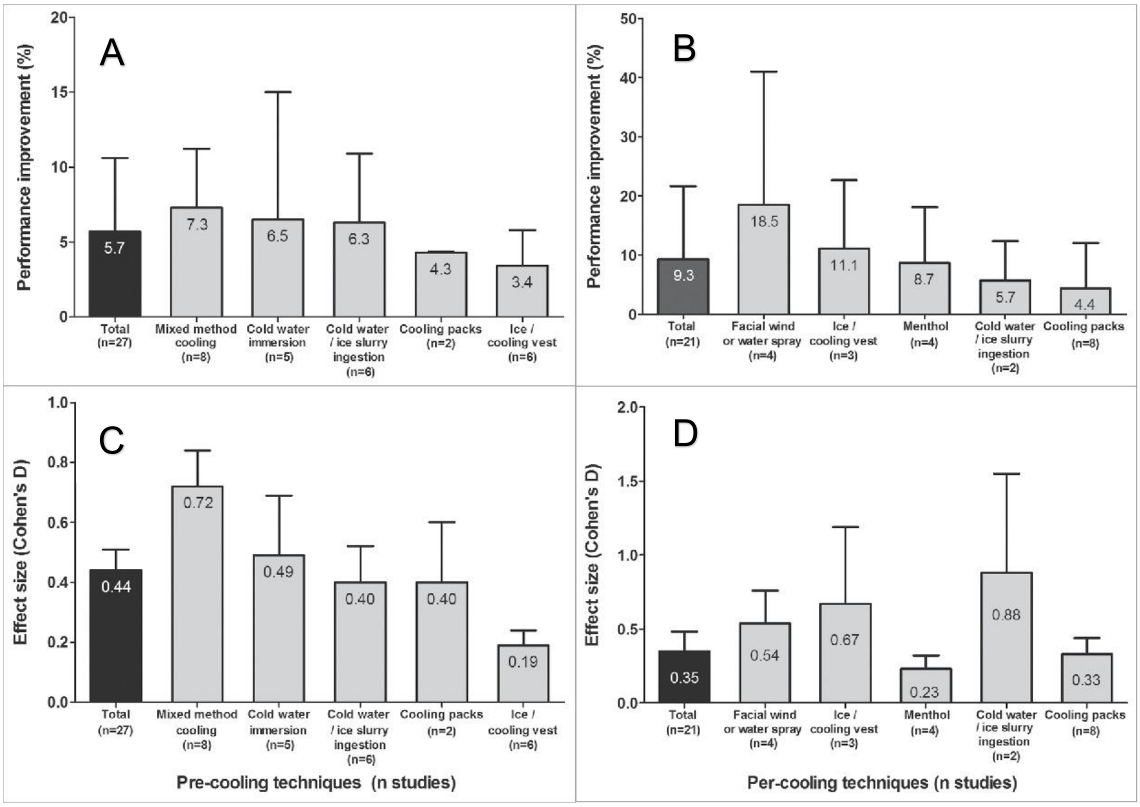


Figure 2.6 An overview of the average pre-cooling performance improvement (%) (A), per-cooling performance improvement (%) (B), effect size (C) of pre-cooling and (D) of per-cooling (black bar) and the beneficial effects of different pre- and per-cooling strategies (grey bars). Data are presented as mean ± standard deviation. Taken from Bongers et al. (2014) and Bongers, Hopman & Eijsvogels (2017).

Perceptual cooling refers to the class of methods that do not lower physiological thermal strain but activate receptors (transient receptor potential cation channel subfamily M member 8 [TRPM8]; also known as the cold and menthol receptor 1) implicated as a primary mechanism of cold somatosensation detection in humans (Andersen et al. 2014). Menthol cooling is the most common and most researched method of perceptual cooling and can be administered through a spray, mouth rinse, or orally consumed (Figure 2.6B and 6d) (Gillis et al. 2016; Mundel & Jones 2010; Riera et al. 2014; Stevens et al. 2017; Stevens et al. 2016; Tran Trong et al. 2015). Despite menthol being a nonthermal cooling strategy, consistent improvements in thermal sensation and comfort have been observed in a dose-response fashion in menthol concentrations from 0.01 – 0.20% (Gillis et al. 2016; Mundel & Jones 2010; Riera et al. 2014; Stevens et al. 2017; Stevens et al. 2016;

Tran Trong et al. 2015). Although benefits have been observed in thermal perception, topical application of menthol has been shown to evoke changes in thermoeffector responses that potentially increase the risk of heat storage and may impair prolonged exercise performance in the heat (Barwood et al. 2020). Athletes and practitioners are advised to carefully test strategies involving topical menthol application prior to competition as thermoeffector changes vary based on surface area, menthol concentration, and site of application (Barwood et al. 2020).

With heightened hyperthermia risk before the Tokyo 2020/1 Olympic Games, institutional resources from national Olympic committees were applied to translating the well-supported cooling protocols in endurance sports to team sport settings in events such as soccer, hockey, baseball, softball, and rugby sevens. Evidence-based protocols will continue to be required that align with the complex competition and scheduling needs of team sport game days in both male and female events to guide best-practice in hot and humid tournament conditions. Currently, the efficacy and external validity of these strategies are unknown in teams sport environments.

HEAT ACCLIMATION

Practitioners can assist athletes to acclimate to heat using any number of endurance-derived protocols supported by the sports science and occupational literature (see Figure 2.7). These strategies are characterised by repeated exposures to a sufficient volume and intensity of heat stress to develop physiological adaptations lowering the homeostatic disruption of future bouts of the same magnitude. These adaptations include increased sweat rate with more dilute composition, expansion of blood plasma volume, enhanced skin blood flow, lower heart rate and core body temperature, and increased production of heat shock proteins (Sawka et al. 2011; Sawka, Wenger & Pandolf 2011). Exposures are either artificial (i.e., heat acclimation; e.g., environmental chamber, additional clothing, hot spa, sauna) or natural (i.e., heat acclimatisation; hot ambient environmental temperatures) (Armstrong & Maresh 1991) in origin. Currently, most of the available evidence is based on findings from endurance athletes performed in laboratories. Whilst controlled settings such as these enable studies to be conducted with a higher level of evidence, applied research with direct application and translation is necessary to determine the generalisability of the findings to diverse and dynamic environments. Laboratory findings such as these are theoretically important, but the transferability to practice is less clear due to contextual factors such as scheduling, training specificity concerns, financial cost, large athlete numbers, and access to equipment or facilities making prolonged exposure to heat training difficult.

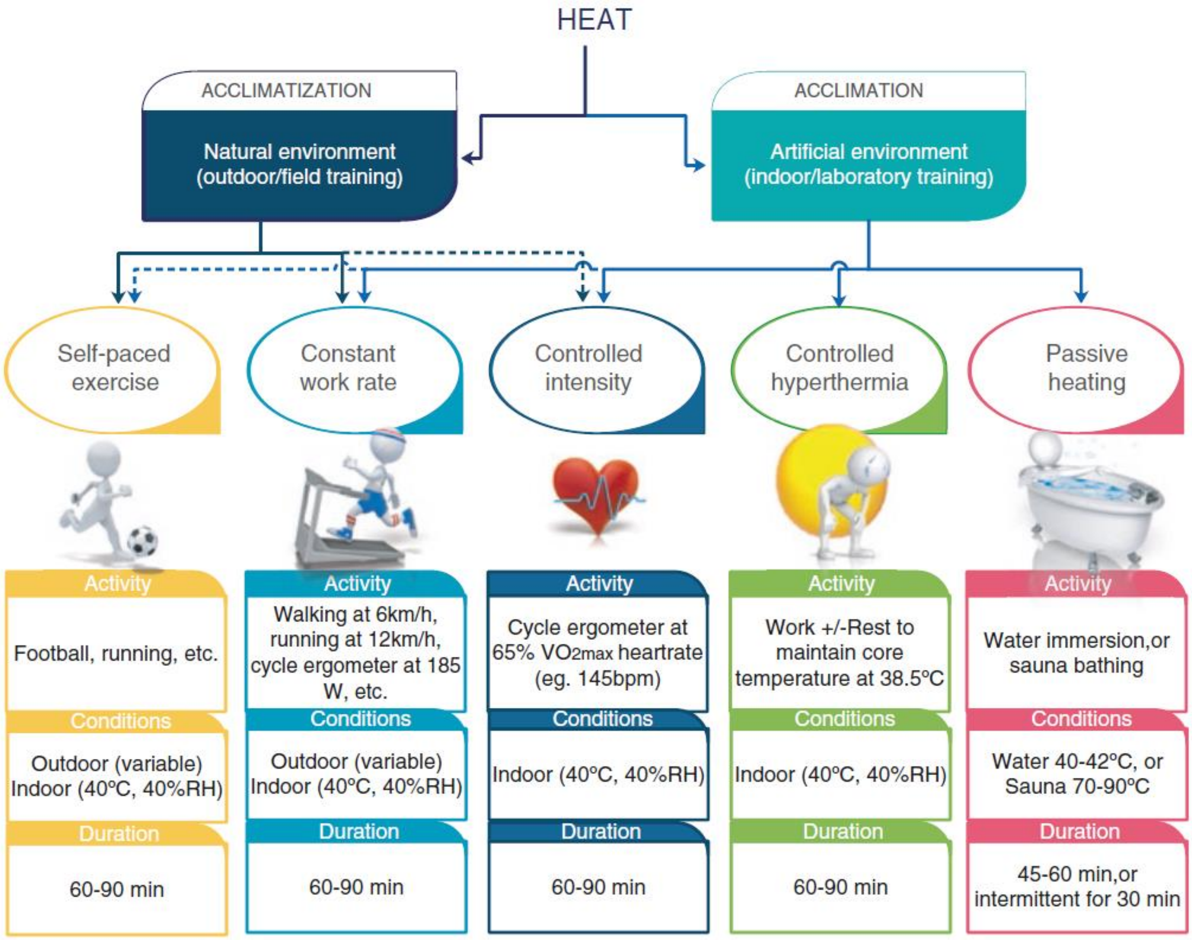


Figure 2.7 Schematic overview of methods for heat acclimation and heat acclimatisation, with examples. Various combinations of temperature and humidity are possible, as well as the use of portable heaters and wearing additional clothing. RH: relative humidity, VO_2max: maximal oxygen uptake. Based on Daanen, Racinais & Périard (2018), taken from Périard & Racinais (2019).

Current research consensus suggests that longer-term heat acclimation/acclimatisation (i.e., heat training) strategies provide the greatest protection against physiological strain and compromised performance during training and competition in the heat (see Figure 2.8) (Racinais, Alonso, et al. 2015; Tyler et al. 2016). Despite a lack of standardisation between HA protocols and research designs, general trends have emerged from the scientific literature that provides a framework to guide practitioners in developing bespoke solutions. These outline recommendations for the frequency, duration, intensity, and type of evidence-based heat training that may develop beneficial physiological heat responses; yet as alluded to above their endurance paradigm origin often lacks transferability into an elite team sport environment, particularly rugby sevens.

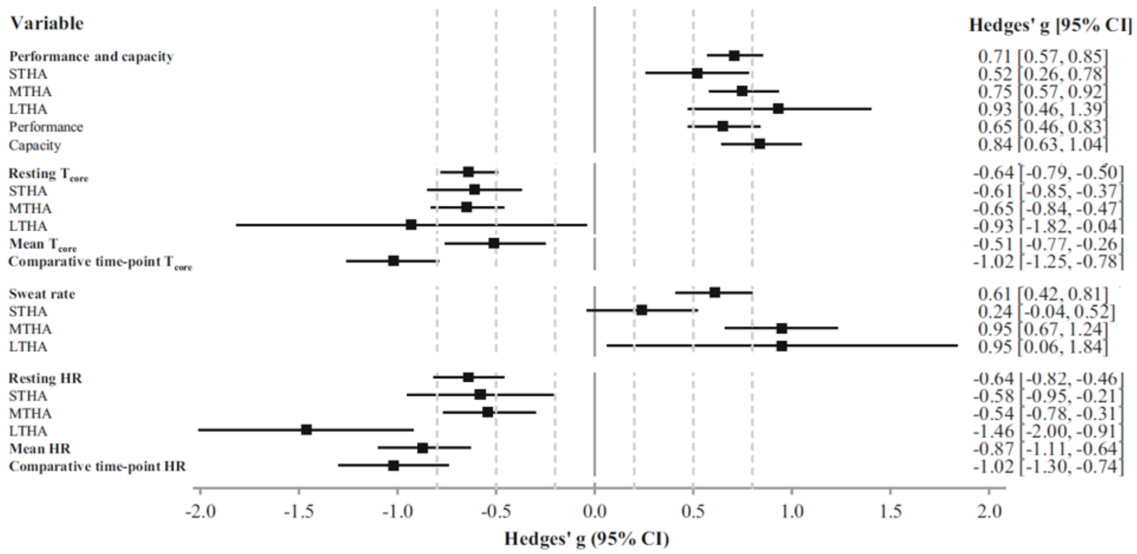


Figure 2.8 Forest plot summarising the effect [±95 % confidence intervals] of heat adaptation on exercise performance and capacity, and on physiological and perceptual responses. Dashed lines denote small (Hedges' g = 0.20 – 0.49), medium (Hedges' g = 0.50 – 0.79) and large (Hedges' g > 0.80) effect sizes. STHA: short-term heat adaptation; MTHA: medium-term heat adaptation; LTHA: long-term heat adaptation; HR: heart rate; T_{core}: core body temperature; Taken from Tyler et al. (2016).

Frequency: Heat training protocols have been classified in research by the frequency of repeated heat exposures into three discrete categories:

- Short-term (< 7 exposures)
- Medium-term (8 – 14 exposures)
- Long-term (> 15 exposures)

Most heat-specific adaptations develop within the first week of heat training and yield slower returns over the following two weeks (Flouris et al. 2014; Ladell 1951; Robinson et al. 1943), although trained athletes develop adaptations much quicker (up to 50% faster) (Pandolf 1979; Pandolf, Burse & Goldman 1977) and can generally optimise cardiovascular, sudomotor, and aerobic responses to hot conditions within two weeks of acclimatisation (Karlsen et al. 2015; Lorenzo et al. 2010; Nielsen et al. 1993; Racinais, Periard, et al. 2015). Short-term protocols offer physiological and performance benefits (e.g., reductions in T_c and HR) (Chalmers et al. 2014) making them a very attractive proposition for commonly time-poor athletes and teams at the elite level; although longer protocols are more commonly advocated as research suggests medium-term exposure schedules are more effective (heightened sweat response in addition to stronger T_c and HR responses) (Guy et al. 2015; Tyler et al. 2016). Exposures can be performed on either consecutive or non-consecutive days as this has been shown to have no meaningful effect on adaptation (Fein, Haymes & Buskirk 1975). Retention of the benefits of heat acclimation appears to remain longer for dry compared to humid heat (Pandolf 1998).

Duration: For heat training to be effective, the prescription dosage must exceed the adaptation threshold of the athlete. This dosage is largely dependent on the duration of exposures, with more pronounced physiological and performance effects observed with longer durations (Tyler 2019; Tyler et al. 2016). A consensus recommendation on training and competing in the heat was published in 2015 recommending at least 60 minutes of heat acclimation/acclimatisation (Racinais, Alonso, et al. 2015), although earlier research proposed 100 minutes (Pandolf 1998) and studies have investigated durations ranging from 27 to 300 minutes (mean ± SD: 105 ± 62 min) (Tyler 2019; Tyler et al. 2016).

Intensity: The intensity of the heat stimulus has been proposed to be a key determinant of the presence of sweat and blood plasma volume adaptations (Tyler 2019). Research studies have investigated a wide range of ambient temperatures (25 – 55°C; mean: 40°C) and relative humidities (13 – 100%; mean: 40%) (Tyler et al. 2016), with optimal prescription related to the current training and acclimatisation status of the athlete. Although training in dry heat improves humid heat performance (Bean & Eichna 1943; Fox et al. 1963) and vice versa (Eichna et al. 1945), some adaptations are specific to the environment such as changes in sweat rate in dry heat and core body temperature in humid heat (Tebeck et al. 2020). Practitioners and athletes are thus recommended to predominantly train in comparable environments to those of the competition (Armstrong & Maresh 1991; Edholm 1966; Hellon et al. 1956; Racinais, Alonso, et al. 2015).

Despite the well-supported evidence outlining endurance-based heat acclimation paradigms, many of the recommendations are simply not possible in a complex team sports preparation scenario given the competing training needs (strength, power, technical skills, speed endurance etc.). Practitioners in team sports environments seeking HA without compromising the holistic training effect require data on the influence of HA solutions more closely aligned with team sports training schedules.

Practitioners and researchers seeking the benefits of effective HA have begun investigating innovative strategies addressing the desire for suitable protocols in team sports. Passive strategies such as hot water immersion (HWI) or sauna now receive interest as a less obtrusive modality to promote HA (i.e., more appropriate for team sport environments) and show potential to heighten the heat tolerance status of partially-acclimated athletes (Heathcote et al. 2018; Kissling, Akerman & Cotter 2020; Zurawlew, Mee & Walsh 2018; Zurawlew et al. 2016). Whilst the current research has been conducted on recreational endurance athletes (limiting the confidence for their effectiveness in elite, partially acclimated team sport athletes), the findings show promise for team sports practitioners unable to use the endurance-based/informed paradigms of heat acclimation. Passive strategies using hot rooms/HWI have been reported to induce beneficial heat responses in performance (Scoon et al. 2007; Zurawlew et al. 2016), thermoregulation (Shido et al. 1999; Zurawlew, Mee & Walsh 2018; Zurawlew et al. 2016), hematology (Beaudin et al. 2009; Bonner et al. 1976; Scoon et al. 2007; Stanley et al. 2015; Zurawlew et al. 2016), and thermal perception (Racinais et al. 2017; Schulze et al. 2015; Young et al. 1987). If found to be effective in elite team sport athletes, passive heat strategies will be highly attractive to coaches and practitioners seeking to diminish any compromised training quality and quantity related to HA. Whilst the empirical support for passive heat acclimation is developing, practitioners working with female athletes currently lack evidence outlining the sex-related effects of these methodologies. Data is required on female subjects to support the development of training programs accounting for the sex-based physiological differences that may predispose females to heightened hyperthermia risk (Janse et al. 2012).

BARRIERS TO PRACTICE / TRANSLATIONAL CHALLENGES

Despite success in other sporting disciplines, practitioners working in female team sports (and team sports more broadly) currently do not have the required evidence to inform best-practice solutions to extremes of heat and humidity within their unique contexts. Females are an understudied population within sports science generally, but particularly in elite-level team sports, representing a significant barrier to evidence-informed practice. Similarly, some legislative and technical advances are required to optimally address some issues, such as in the case of pre-cooling [laws and regulations of the sport, time pressure before games or at half time, excess weight, and skin irritation (Arngrímsson et al. 2004)].

Like much of sports science research, many studies on thermal exercise physiology in elite athletes are limited by very small sample sizes (Skorski & Hecksteden 2021), incomplete heat acclimation/acclimatisation (Petersen et al. 2010), or inappropriate measurements (Casa et al. 2007). Nevertheless, the current research available provides valuable support and rationale for practitioners and researchers developing progressive research designs to address the paucity of data surrounding elite, female, team sport athletes. If appropriately addressed, and robust evidence is provided, practitioners will be enabled to tailor solutions for this understudied population of athletes competing in hot and humid competition conditions.

CHAPTER 3 | CORE BODY TEMPERATURE IN INTERMITTENT SPORTS: A SYSTEMATIC REVIEW

Henderson, M.J., Grandou, C., Chrismas, B.C.R., Coutts, A.J., Impellizzeri, F.M. & Taylor, L. (2023). Core body temperature in intermittent sports: A systematic review. *Sports Medicine*, In press.

ABSTRACT

Background: Hyperthermia (and associated health and performance implications) can be a significant problem for athletes and teams involved in intermittent sports. Quantifying the highest thermal strain (i.e., peak T_c) from a range of intermittent sports would enhance the knowledge of the thermal demands of sport and eventually inform decisions regarding the need for training or match-day interventions to minimise thermally mediated harm and/or performance reductions. **Objective:** The objective of this systematic review was to synthesise and characterise the available thermal strain data collected in competition from intermittent sport athletes. **Methods:** A systematic literature search was performed on Web of Science, MEDLINE, and SPORTDiscus to identify studies up to 7th January 2021. Electronic databases were searched using a text mining method to provide a partially automated and systematic search strategy retrieving terms related to T_c measurement and intermittent sport. Records were eligible if they included T_c measurement during competition (without intervention) in healthy, adult, intermittent sport athletes at any level. Due to the lack of an available tool that specifically includes potential sources of bias for physiological responses in descriptive studies, a methodological evaluation checklist was developed and used to document important methodological considerations. Data were not meta-analysed given the methodological heterogeneity between studies and therefore were presented descriptively in tabular and graphical format. **Results:** A total of 31 studies were selected for review; 26 were observational, two were experimental (both randomised controlled trials), and three were quasi-experimental (two repeated measures designs and one non-randomised controlled trial). Across all included studies, 350 participants (plus not reported participant numbers for two studies) were recruited after accounting for shared data between studies. Three studies (~10%) found no evidence of hyperthermia, 22 (~71%) found evidence of 'modest' hyperthermia (T_c between 38.5°C and 39.5°C), and six (~19%) found evidence of 'marked' hyperthermia (T_c of 39.5°C or greater) during intermittent sports competition. **Conclusions:** Practitioners and coaches supporting intermittent sport athletes are justified to seek interventions aimed at mitigating the high heat strain observed in competition. More research is required to determine the most effective interventions for this population that are practically viable in intermittent sports settings (that are often constrained by many competing demands). Greater statistical power and homogeneity among studies are required to quantify the independent effects of wet bulb globe temperature, competition duration, sport, and level of competition on peak T_c, all likely to be key modulators of the thermal strain experienced by competing athletes. **Funding** Mitchell Henderson is supported by the Australian Government's Research Training Program scholarship. There were no other funders or sponsors for this review. **Registration** This systematic review was registered on the open science framework (https://osf.io/vfb4s; DOI: 10.17605/OSF.IO/EZYFA, 4th January 2021).

INTRODUCTION

Heat and temperature affect all biological systems; impacting the successful development, maturation, and functioning of even the most basic units of life (Leuenberger et al. 2017). In humans, changes of several degrees in T_c away from a narrow homeostatic range [mean: 36.6°C (95% CI: 35.7 – 37.3°C)] (Obermeyer, Samra & Mullainathan 2017) can be fatal (Charkoudian 2010; Lim, Byrne & Lee 2008). When working (Taylor 2006) or exercising (Brotherhood 2008) in hot conditions, heat gain often exceeds loss, allowing heat to accumulate in the body and T_c to rise. This may lead to hyperthermia and associated reductions in physiological (Cheuvront et al. 2010) and cognitive performance (Nybo 2008). Further, increases in T_c (particularly in combination with dehydration) heighten the risk of exertional heat illness/stroke (EHI/S) (Armstrong et al. 2007; Bouchama & Knochel 2002), which has been proven fatal during occupational pursuits (Kark et al. 1996), and recreational (Binkley et al. 2002) and professional sport (Casa et al. 2005). Large international sporting competitions played in thermally stressful conditions such as the World Athletics Championships (Bermon & Adami 2019; Racinais et al. 2019; Racinais et al. 2021), Olympic Games (Gerrett et al. 2019; Kissling, Akerman

& Cotter 2020; Racinais & Ihsan 2020; Racinais & Périard 2020; Taylor, Carter & Stellingwerff 2020), and the International Federation of Association Football (FIFA) World Cup (Matzarakis & Fröhlich 2015; Sofotasiou, Hughes & Calautit 2015) have intensified the research interest, as policymakers seek to ensure event safety; and athletes/practitioners seek to limit heat-mediated reductions in performance. Understanding the risk and prevalence of high thermal strain and/or hyperthermia in certain sports informs risk mitigation, education, and training strategies aimed to protect athlete health and maximise performance.

When athletes perform or train in thermally challenging conditions, they are subject to added physiological strain when compared to the same work in temperate conditions (Ely et al. 2007; Guy et al. 2015; McArdle 1981; Tyler et al. 2016). Endurance exercise performance is particularly compromised by high thermal strain (i.e., high T_c) due to cardiovascular adjustments (simultaneously supporting thermoregulation and oxygen delivery), cerebral function changes, muscle metabolism alterations, and central nervous system perturbations (Nybo, Rasmussen & Sawka 2014). In comparison to endurance events, the effects of thermal strain on performance in intermittent sports are less understood. This is likely due to the complexity of intermittent sport movement patterns and limits in practice/equipment available to athletes and support staff. High-level intermittent sport athletes consistently generate T_c above 39°C during competition regardless of the ambient environmental conditions (T_c up to 40.5°C have been observed in athletes when competing in hot conditions (Aughey, Goodman & McKenna 2014) and up to 39.8°C when competing in cool conditions (Henderson et al. 2020)) (Nybo et al. 2013). Elevation of T_c is likely to enhance performance in single-sprint events as a result of changes in phosphocreatine utilisation (Gray et al. 2006), adenosine triphosphate turnover (Febbraio et al. 1996), and increased muscle fibre conduction velocity (Farina, Arendt-Nielsen & Graven-Nielsen 2005). Despite this, repeated-sprint (< 60 s between efforts) (Drust et al. 2005; Girard, Brocherie & Bishop 2015), intermittent-sprint (60-300 s between efforts) (Sunderland & Nevill 2005), and neuromuscular performances (Morrison, Sleivert & Cheung 2004; Nybo & Nielsen 2001) are impaired when thermal strain is severe (T_c >39°C). These reductions are related to accelerated declines in cardiac output (Coyle & González-Alonso 2001), central nervous system output (Tucker et al. 2004), perfusion pressure (González-Alonso et al. 2004), and blood flow in the exercising muscles (causing greater reliance on anaerobic energy contribution and associated metabolic acidosis) (Sawka et al. 2011). Work rate during self-paced tasks is also voluntarily reduced under conditions of high thermal stress (Tucker et al. 2006; Tucker et al. 2004) due to an integrated protective behavioural response governed by effort and thermal perceptions (Flouris & Schlader 2015). The combined autonomic and behavioural responses to high thermal strain (and their associated impact on physical performance) potentially endanger the health and competition outcomes in intermittent sports.

Further to the physical impairments resulting from excessively high T_c, heat strain can also compromise cognitive function (Hancock & Vasmatzidis 2003) and exacerbate mental fatigue (Schmit et al. 2017). Cognition supports decision-making in sports as athletes are required to process task-specific information from their competitive environment and match sensory inputs with appropriate action (Lex et al. 2015). Although small improvements in cognitive function are common after moderate T_c increases (potentially due to increased arousal (McMorris et al. 2006) or cerebral blood flow (Grego et al. 2004)) (Bandelow et al. 2010; Schlader et al. 2015; Simmons et al. 2008), severe thermal strain has been observed to impair cognitively complex task performance in occupational (Gaoua et al. 2018; Morley et al. 2012; Schlader et al. 2015) and athletic populations (Donnan, Williams & Stanger 2020). The current theory suggests this is related to both hyperthermia and cognitive tasks competing for finite cerebral resources (cortical activity (De Pauw, Roelands, Marusic, et al. 2013; Nybo & Nielsen 2001) and output intensity from the prefrontal cortex (Olausson et al. 2005; Schmidt et al. 2012)), and performance declines when these capacities are overloaded by complex tasks (Gaoua et al. 2018). High heat strain decreases vigilance and reaction test performance (Faerevik & Reinertsen 2003); and increases perceptions of fatigue and discomfort (Caldwell et al. 2011; Tyler & Sunderland 2008), frequency of unsafe behaviours (Ramsey et al. 1983), and error rates in a visual-motor tracking test (Allan & Gibson 1979), flight simulator (Gibson et al. 1980), and pilots in flight (Froom et al. 1993). Mental fatigue resulting from hyperthermia can lead to further reductions in tactical performance (Smith et al. 2016) and has also been shown to impair technical skill execution (Badin et al. 2016), both accepted constructs of intermittent sports performance (Carling 2013; Impellizzeri & Marcora 2009) and key differentiators of success (Kempton, Sirotic & Coutts 2017; Russell & Kingsley 2011). Combined, these cognitive impairments have the potential to threaten the health and performance of athletes in competition (where execution of cognitively complex tactical decision-making and technically complex skills are frequent and have a large influence on match outcomes (Young et al. 2020)).

Hyperthermia (and associated health and performance implications) can be a significant problem for athletes and teams involved in intermittent sports. Quantifying the peak T_c from a range of intermittent sports would enhance the knowledge of the thermal demands of sport and eventually inform decisions regarding the need for training or match-day interventions to minimise thermally mediated harm and/or performance reductions. The efficacy of applied heat acclimation/acclimatisation training interventions (Tyler et al. 2016) and acute mixed-method cooling protocols (Taylor, Carter & Stellingwerff 2020) is supported by a considerable body of evidence (Racinais, Alonso, et al. 2015). Therefore, with increasing globalisation in sport enabling year-round competition in warmer climates and the ongoing effects of climate change (Brocherie, Girard & Millet 2015), best practice management of exercise-induced hyperthermia (through targeted application of these interventions) will be of increasing importance. Identifying appropriate action by athletes and support staff should be guided by available peer-reviewed literature, and currently, no reviews of the literature provide a synthesis of the thermal strain data collected in-competition during intermittent sports. Further, increased understanding of the magnitude of thermal strain in competing athletes could be used to guide policy surrounding thermoregulatory health and safety at sporting events. We, therefore, systematically reviewed the literature investigating athletes' peak T_c during competition in a variety of intermittent sports. The purpose of this review is to provide athletes, practitioners, and policy makers a synthesis of the core temperature literature to determine the need for interventions aimed at mitigating exercise-induced hyperthermia in intermittent sport athletes.

METHODS

This review was conducted and reported according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al. 2021). A systematic review protocol that included the review question, search strategy, and exclusion criteria was registered with the Open Science Framework (https://osf.io/vfb4s;

DOI: 10.17605/OSF.IO/EZYFA, 4th January 2021).

ELIGIBILITY CRITERIA

Eligibility criteria were drafted and subsequently refined by three authors (MH, FMI, LT) using a random sample of studies. For this review, intermittent sport was operationally defined as all sports characterised by intermittent bursts of high-intensity exercise and requires the execution of complex sport-specific skills and cognitive tasks over a more prolonged period (minutes to hours), with longer breaks at scheduled intervals (e.g., quarters, half time) as well as unscheduled times (e.g., injury or restarting play after scoring in soccer or rugby) (Baker et al. 2015). Studies were considered eligible if they included healthy male or female athletes competing in intermittent sports competitions at any level. Non-human subjects, youth athletes (study participants' mean age minus 2 standard deviations is less than 16 years), or participants with chronic disease, metabolic disorders or injury were excluded. Participants under the age of 16 may have different physiological responses to sports compared to adults and therefore were studied separately. Interventions aimed at both adult and youth athletes were included only if the data provided for adults was reported separately. All exposures including athletes involved in real (i.e., not simulated) intermittent sport (competitive, friendly, or experimental) played within its full parameters (e.g., field size, playing numbers, duration) were included in this review. Outcomes of interest included only internally measured T_c (i.e., gastrointestinal or rectal; shown to display acceptable agreement (Teunissen et al. 2012)). Non-invasive methods were not included due to the lack of acceptable agreement with the internal measures in oesophageal (Teunissen et al. 2012), tympanic (Huggins et al. 2012), and thermal imaging methods (Fenemor et al. 2020). Other markers of thermal strain such as T_{sk} were not included due to the limited availability of competition data (likely due to difficulty in measurement during intermittent sport competition). No limitations were placed on the study design if the intervention met the eligibility criteria. Studies were included only if T_c was measured during competition without intervention (e.g., control condition in intervention studies).

SEARCH

A literature search was conducted by one author (MH) in the electronic bibliographic databases of Web of Science Core Collection, Ovid MEDLINE, and EBSCOhost SPORTDiscus. Databases were searched from inception up until January 2021. No language or publication status restrictions were imposed on the search to ensure literature saturation. Literature search strategies were developed using search terms related to T_c measurement and intermittent sports competition. The keywords were derived using the {litsearchr} package (Grames et al. 2020) in R statistical software (R Core Team 2022) as has been described previously (Grames et al. 2019). The {litsearchr} package uses text mining and keyword co-occurrence networks to efficiently identify potential keywords without relying on a potentially biased set of preselected articles, resulting in the development of a partially-automated and systematic search strategy (Grames et al. 2019). The code used to derive the keywords and Boolean search string are available (https://osf.io/xam5v). The Boolean search string used on all databases with results is provided as an appendix. Trial/study registries were searched during a pilot phase, however, due to the non-clinical nature of this review, no results were found. In conjunction with the database searches, the reference lists of relevant studies, reviews, and books were screened for possible omissions. Relevant experts in the field were also consulted and their profiles were searched to ensure saturation of the literature.

STUDY SELECTION

Articles retrieved through the systematic search were exported into a reference management software (EndNote version X8) and all duplicate articles were removed. All references were then imported into Covidence (Covidence Systematic Review Software, Veritas Health Innovation, 2013) for assessment of eligibility. Two authors (MH, CG) independently screened the records by title and abstract, with all potentially eligible references proceeding to full-text screening with conflicts resolved by a third author (FMI). Authors (MH, CG) then independently screened the full text of all included articles against the eligibility criteria. Interrater reliability, as measured by Cohen's Kappa (κ), was 0.73 during the title and abstract screening and 0.83 during full-text screening.

DATA EXTRACTION

Data were extracted by two authors (MH, CG) and imported into an Excel spreadsheet created for this review. Extracted data were compared with any discrepancies resolved through discussion. Information extracted from each eligible study included publication details (author, year), participant characteristics (sex, level of competition, sample size), study methods (design, types of measurement, recording frequency), exposure (sport, competition type, duration, environmental conditions, location of data collection, home location of participants), and effect measure (T_c).

DATA SYNTHESIS

Data were not meta-analysed given the methodological heterogeneity between studies (including differing T_c measurements, environmental conditions, and exposure durations to a variety of sports). We anticipated based on a scoping search that the statistical heterogeneity could not be explored given that sub-group analyses would leave too few studies in each group for investigating the different moderators. Data were therefore presented descriptively in tabular (Table 3.1) and graphical (Figures 3.4 and 3.5) format.

Figure 3.4 shows the mean T_c for each study condition with confidence intervals (50, 80, 95, and 99%) and contextual information (number of observations and environmental conditions), grouped by sport, and compared to homeostatic (Obermeyer, Samra & Mullainathan 2017) and hyperthermic (Nybo, Rasmussen & Sawka 2014) ranges. Standard deviations for T_c were either reported in text or able to be extracted from figures in all but two studies (see Figure 3.4 caption for details), and these were converted to standard errors by dividing by the square root of the sample size. Standard errors were subsequently converted to confidence intervals by multiplying by the Z-value associated with the desired level of confidence ($Z = 0.674$, 1.282, 1.960, and 2.576 for 50, 80, 95, and 99% confidence intervals, respectively). Finally, adding or subtracting the resulting values from the mean provided upper or lower confidence limits. All studies and group conditions included in the review that reported parametric measures of centrality and variability (mean and standard deviation) were included in the synthesis displayed in Figure 3.4. One study that reported mean values, but not standard deviations, is included but without confidence intervals. Figure 3.4, therefore includes data from 33 group conditions from 30/31 included studies (~97%).

Figure 3.5 shows the relationship between competition duration, wet bulb globe temperature (WBGT), number of observations, and peak T_c between study groups. All studies that provided (1) competition duration and (2) WBGT or ambient temperature and relative humidity were considered eligible for the synthesis displayed in Figure 3.5. Seven studies did not report WBGT, so estimates were calculated using the validated Liljegren method (Liljegren et al. 2008). In the case of a maximum WBGT threshold being reported (e.g., < 18°C), the upper limit was used. In the case of a WBGT range being reported (min – max), the midpoint of the range was used. Data for Stay et al. (2018) could not be included due to not reporting an absolute competition duration. Data from Delamarche et al. (1987), Kouassi et al. (2019), and Mohr et al. (2004) also couldn't be included due to insufficient environmental data being reported to calculate a WBGT estimate. Figure 3.5, therefore, includes data from 28 group conditions from 27/31 (~87%) included studies. In both figures 3.4 and 3.5, when shared data were used between studies, the study that reported the largest sample size for a given condition was used to prevent duplicate data from being visualised.

RISK OF BIAS ASSESSMENT

The current review focused on a specific measure (T_c) as measured in a control (non-experimentally manipulated) condition. Accordingly, no available tool, to our knowledge, specifically includes potential sources of bias for physiological responses in such a (descriptive) context. We, therefore, developed and used a methodological evaluation checklist to document what we deemed to be important methodological considerations for researchers conducting future investigations.

METHODOLOGICAL EVALUATION CHECKLIST

A. Clearly described population (age, sex, and level of competition)
B. Environmental information reported (wet bulb globe temperature [WBGT] or ambient temperature and relative humidity; must be on a continuous scale and not made discrete such as < 18°C).
C. Information regarding the inclusion of substitutes or time spent out of competition for participants reported (if sport includes substitutes)

D. Stating the duration of gastrointestinal device ingestion before the measurement period (when a gastrointestinal device is used)

E. Control of cold or hot food/beverage consumption during the measurement period (if the duration of gastrointestinal pill ingestion is less than 5 hours)

F. Reporting of menstrual cycle phase in female athletes

G. Continuous measurement of T_c (as opposed to discrete time points, e.g., pre-, and post-match)

H. Reporting tests/checks for normality of data

I. Missing data addressed and justified (if present)

RESULTS

STUDY SELECTION

The initial database search yielded 2,113 studies. Once duplicates were removed, 1,428 titles and abstracts were screened for inclusion and of those 1,368 studies were excluded based on the eligibility criteria. A total of 59 studies were retrieved as full text and assessed for eligibility (one report not retrieved (Sugiyama & Kawai 1997)), and of those, 30 were excluded (reasons for the exclusion provided in Figure 3.1). An additional two studies that met the inclusion criteria were identified by searching reference lists. Upon completion of these procedures (Figure 3.1), 31 studies were included for analysis in this systematic review (Table 3.1).

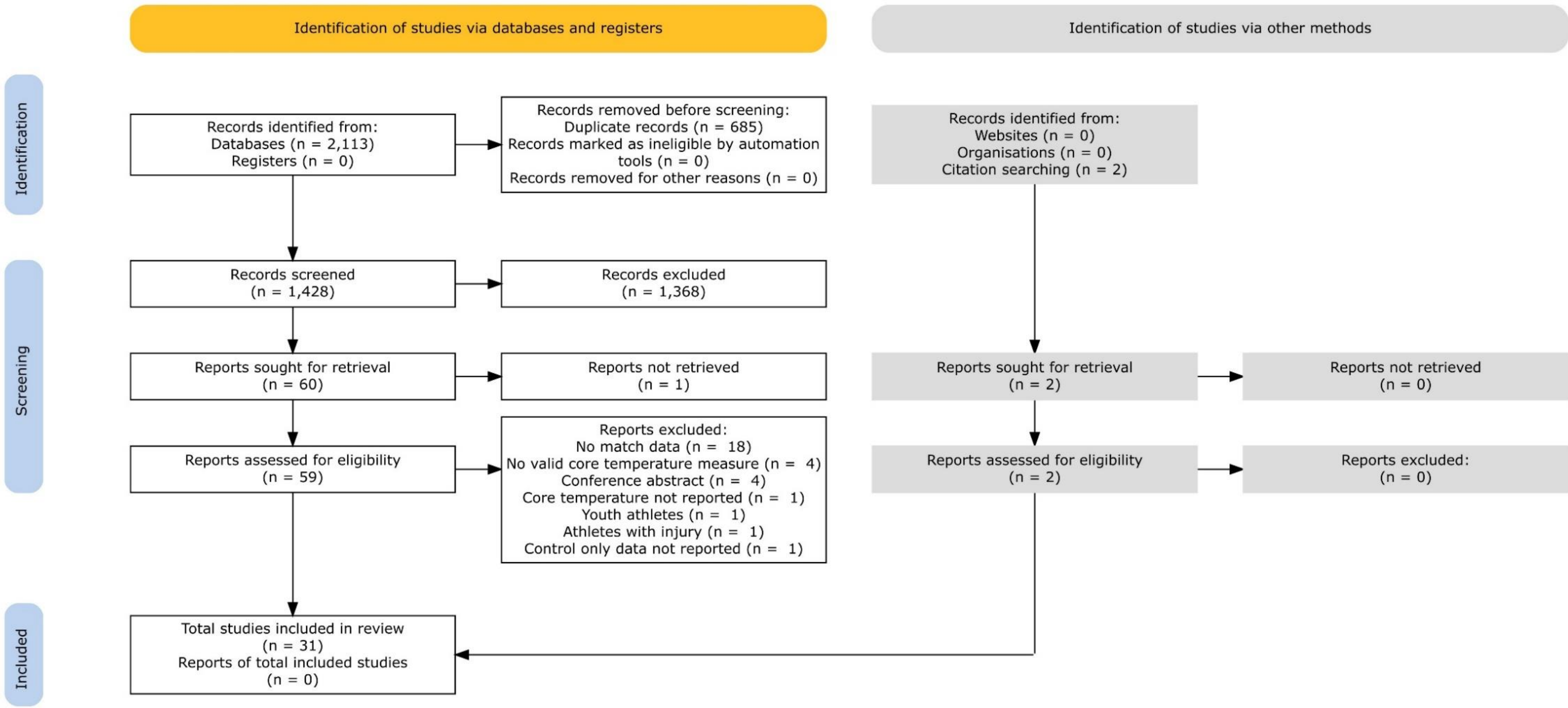


Figure 3.1 PRISMA flow diagram of systematic search and included studies.

CHARACTERISTICS OF THE PUBLICATIONS

The studies were published between 1972 and 2020 (Figure 3.2A) in 10 different sports (Figure 3.2B), 12 different countries (Figure 3.2C), and 15 different peer-reviewed journals (Figure 3.2D). Six studies were published in a British Journal of Sports Medicine supplement focused on heat stress and tennis performance in April 2014 (Girard et al. 2014; Girard, Racinais & Périard 2014; Knez & Périard 2014; Périard, Girard & Racinais 2014; Périard et al. 2014a, 2014b). The key characteristics of each study are presented in Table 3.1.

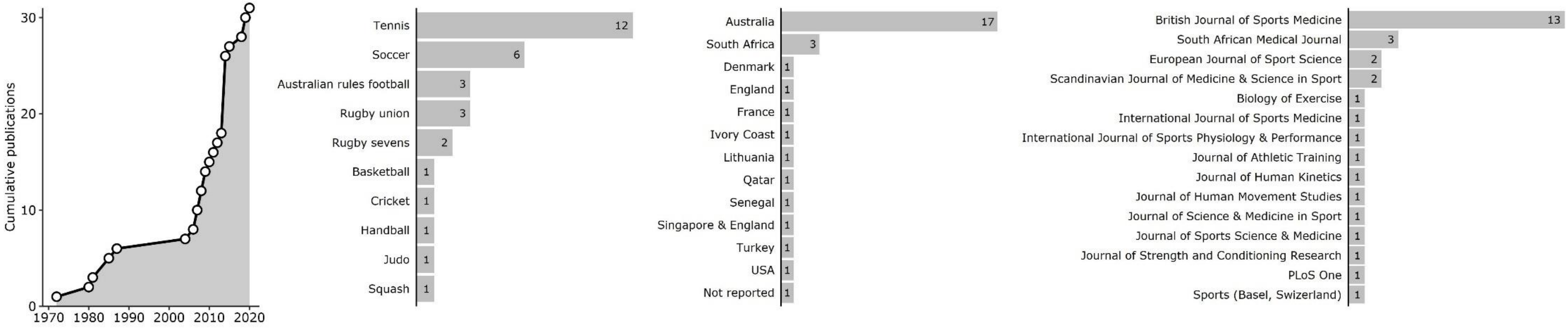


Figure 3.2 Publication characteristics of the included studies. Cumulative number of publications over time (3.2A), count of included studies by sport (3.2B), country (3.2C), and by the journal (3.2D).

Table 3.1 Descriptive results and characteristics of included studies.

Author/s	Study Design	Participants	Sport	Level of competition	Measurement type	Activity	Environmental conditions	Peak T_c
Aughey, Goodman & McKenna (2014)	Observational	35 M	Australian rules football	Level 5	Gastrointestinal	8 hot matches [HOT] 8 cool matches [COOL] (friendly and competitive)	WBGT: HOT = 28°C (3); COOL = <18°C Ambient temperature: HOT = 27°C (2); COOL = 17°C (4) Relative humidity: HOT: 58% (15); COOL: 51% (11)	HOT: 39.5°C (0.5) COOL: 39.4°C (0.6)
Blanksby et al. (1980)	Observational	27 M	Squash	Levels 1, 2, and 5	Rectal	27 experimental matches (9 matches of each 3 playing standards)	Ambient temperature: < 22.2°C Relative humidity: < 60%	A grade: 39.14°C Active: 38.87°C Sedentary: 38.90°C
Cohen et al. (1981)	Observational	15 M	Rugby union	Levels 1, 2, and 3	Rectal	1 competitive match	Ambient temperature: 24.5°C Relative humidity: 31%	39.4°C (0.5)
Dancaster (1972)	Observational	Not reported	Rugby union	Level 2	Rectal	5 competitive matches	WBGT: 20.5°C (2.7) Ambient temperature: 19 – 34.5°C	39.6°C (0.8)
Delamarche et al. (1987)	Observational	6 M	Handball	Level 5	Rectal	1 experimental match	Ambient temperature: 18 – 20°C	39.42°C (0.31)
Diaw et al. (2014)	Experimental (RCT)	11 M (control group only)	Soccer	Level 2	Rectal	2 experimental matches	Ambient temperature: 24.5 – 25°C Relative humidity: 65 – 68%	37.28°C (0.61)

Author/s	Study Design	Participants	Sport	Level of competition	Measurement type	Activity	Environmental conditions	Peak T_c
Duffield et al. (2013)	Quasi-experimental (Repeated measures)	7 M (control match only)	Soccer	Level 5	Gastrointestinal	1 competitive match (recorded for 5 matches)	WBGT: 26°C (2) Ambient temperature: 27°C (2) Relative humidity: 80% (10)	39.92°C (0.42)
Duffield, Coutts & Quinn (2009)	Observational	10 M	Australian rules football	Level 5	Gastrointestinal	2 friendly matches	WBGT: 27.6°C (2.3) Ambient temperature: 29.5°C (1.3) Relative humidity: 64.9% (16.7)	39.5°C (0.4)
Edwards & Clark (2006)	Observational	15 M	Soccer	Levels 2 and 5	Gastrointestinal	2 friendly matches (1 recreational; 1 professional)	Ambient temperature: 16°C (recreational) & 19°C (professional) Relative humidity: 47% (recreational) & 53% (professional)	Recreational: 39.4°C (0.5) Professional: 38.8°C (0.4)
Elliott, Dawson & Pyke (1985)	Observational	8 M	Tennis	Level 3	Rectal	4 experimental matches	WBGT: 21.5°C (1.9) Ambient temperature: 22.7°C (1.8) Relative humidity: 64.3% (7.2)	38.5°C (0.4)
Girard et al. (2014)	Observational	12 M	Tennis	Level 4	Rectal	2 experimental matches each (1 in hot conditions [HOT]; 1 in cool conditions [COOL])	WBGT: HOT = 33.6°C (0.9); COOL = 19.4°C (0.3) Ambient temperature: HOT = 36.8°C (1.5); COOL = 21.8°C (0.1) Relative humidity: HOT = 36.1% (11.3); COOL = 72.3% (3.2)	HOT: 39.4°C (0.5) COOL: 38.7°C (0.2)
Girard, Racinais & Périard (2014)	Observational	12 M	Tennis	Level 4	Rectal	2 experimental matches each (1 in hot conditions [HOT]; 1 in cool conditions [COOL])	WBGT: HOT = 33.6°C (0.9); COOL = 19.4°C (0.3) Ambient temperature: HOT = 36.8°C (1.5); COOL = 21.8°C (0.1) Relative humidity: HOT = 36.1% (11.3); COOL = 72.3% (3.2)	HOT: 39.4°C (0.5) COOL: 38.7°C (0.2)
Goodman, Cohen & Walton (1985)	Observational	Not reported	Rugby union	Level 2	Rectal	3 competitive matches	Ambient temperature: 17.8 – 22.6°C Relative humidity: 18 – 85%	39.17°C (0.06)

Author/s	Study Design	Participants	Sport	Level of competition	Measurement type	Activity	Environmental conditions	Peak T_c
Henderson et al. (2020)	Observational	12 F	Rugby sevens	Level 5	Gastrointestinal	3 competitive matches	WBGT: 18.9 – 20.1°C	39.2°C (0.5)
Hornery et al. (2007)	Observational	14 M	Tennis	Level 4	Gastrointestinal	33 competitive matches (2 hard court tournaments; 1 clay tournament)	Ambient temperature: Hard court = 32.0 (4.5); Clay = 25.4 (3.8) Relative humidity: Hard court = 38 (14); Clay = 32 (5)	Hard court: 38.9 (0.3) Clay: 38.5 (0.6)
Knez & Périard (2014)	Observational	10 M	Tennis	Level 4	Rectal	2 experimental matches each (1 in hot conditions [HOT]; 1 in cool conditions [COOL])	WBGT: HOT = 33.6°C (0.9); COOL = 19.5°C (0.3) Ambient temperature: HOT = 36.7°C (1.6); COOL = 21.8°C (0.1) Relative humidity: HOT = 35.9% (11.9); COOL = 73.3% (2.9)	HOT: 39.3° (0.5) COOL: 38.7° (0.2)
Kouassi et al. (2019)	Quasi-experimental (NRCT)	20 F&M (control group only)	Judo	Level 4	Rectal	20 competitive bouts	Not reported	38.3 (0.3)
Mohr et al. (2004)	Experimental (RCT)	16 M Control (n = 8) Re-warmup (n = 8)	Soccer	Level 4	Rectal	1 experimental match	Not reported	Control: 38.9 (0.1) Re-warmup: 39 (0.2)
Mohr et al. (2012)	Quasi-experimental (Repeated measures)	17 M	Soccer	Unclear	Gastrointestinal (7) & rectal (10)	2 experimental matches (1 in hot conditions [HOT]; 1 in control conditions [CON])	Ambient temperature: HOT = 43°C; CON = 21°C Relative humidity: HOT = 12%; CON = 55%	HOT: 39.7 (0.41) CON: 38.8 (0.82)
Morante & Brotherhood (2008a)	Observational	6 F&M	Tennis	Level 2	Rectal	6 experimental matches	Not reported	38.31°C

Author/s	Study Design	Participants	Sport	Level of competition	Measurement type	Activity	Environmental conditions	Peak T_c
Morante & Brotherhood (2008b)	Observational	6 F 19 M	Tennis	Levels 2 and 4	Rectal	47 experimental matches	WBGT: 22.5°C (4.3) Ambient temperature: 25.0°C (5.4) Relative humidity: 50.7% (14.3)	38.72 (0.38)
Morante & Brotherhood (2007)	Observational	6 F 19 M	Tennis	Level 2	Rectal	43 experimental matches	WBGT: elite [F = 24.4°C (4.9), M = 23.0°C (3.0)]; recreational [F = 20.9°C (6.2), M = 22.1°C (4.7)] Ambient temperature: elite [F = 26.9°C (6.4), M = 25.0°C (3.8)]; recreational [F = 23.3°C (7.1), M = 24.9°C (6.4)]	Elite: F = 38.4°C (0.3); M = 38.5°C (0.4) Recreational: F = 38.2°C (0.3); M = 38.4°C (0.4)
Ozgunen et al. (2010)	Observational	10 M	Soccer	Level 4	Gastrointestinal	2 experimental matches	Ambient temperature: Match 1 = 34°C (1); Match 2 = 36°C (0) Relative humidity: Match 1 = 38% (2); Match 2 = 61% (1)	Match 1: 39.1°C (0.4) Match 2: 39.6°C (0.3)
Périard et al. (2014a)	Observational	10 M	Tennis	Level 4	Rectal	2 experimental matches each (1 ad libitum fluid consumption [HOT]; 1 with hydration plan [HYD])	WBGT: HYD = 35.2°C (2.4); HOT = 34.2°C (0.4) Ambient temperature: HYD = 36.9°C (2.3); HOT = 36.8°C (0.3) Relative humidity: HYD = 32.5% (12.8); HOT = 33.3% (3.8)	HOT: 39.4°C (0.5) HYD: 39.2°C (0.6)
Périard et al. (2014b)	Observational	12 M	Tennis	Level 4	Rectal	2 experimental matches each (1 in hot conditions [HOT]; 1 in cool conditions [COOL])	WBGT: HOT = 33.6°C (0.9); COOL = 19.4°C (0.3) Ambient temperature: HOT = 36.8°C (1.5); COOL = 21.8°C (0.1) Relative humidity: HOT = 36.1% (11.3); COOL = 72.3% (3.2)	HOT: 39.4°C (0.5) COOL: 38.7°C (0.2)
Périard, Girard & Racinais (2014)	Observational	12 M	Tennis	Level 4	Rectal	2 experimental matches each (1 in hot conditions [HOT]; 1 in cool conditions [COOL])	Ambient temperature: HOT = 36.8°C (1.5); COOL = 21.8°C (0.1) Relative humidity: HOT = 36.1% (11.3); COOL = 72.3% (3.2)	HOT: 39.4°C (0.5) COOL: 38.7°C (0.2)
Pliauga et al. (2015)	Observational	10 M	Basketball	Level 3	Rectal	1 experimental match	Not reported	39.4°C (0.4)

Author/s	Study Design	Participants	Sport	Level of competition	Measurement type	Activity	Environmental conditions	Peak T_c
Stay et al. (2018)	Observational	38 M	Cricket	Level 4	Gastrointestinal	6 competitive 4-day matches	WBGT: Batters = 23.7 (IQR: 15.6 – 31.8); fielders = 24.2 (IQR: 17.0 – 31.4) Ambient temperature: Batters = 27.6 (range: 22.4 – 32.8); fielders = 27.7 (range: 20.9 – 34.5) Relative humidity: Batters: 52.7 (range: 35.6 - 69.8); fielders: 48.1 (range: 34.9 – 61.3)	Batters: 38.5 (IQR: 37.7 – 39.3) Fielders: 38 (IQR: 37.3 – 38.7)
Taylor, Thornton, et al. (2019)	Observational	17 M	Rugby sevens	Level 5	Gastrointestinal	11 competitive matches	WBGT: 22.1°C (4.9)	38.5°C (0.6)
Tippet et al. (2011)	Observational	7 F	Tennis	Level 5	Gastrointestinal	7 competitive matches	WBGT: 30.3°C (2.3)	39.13°C (0.34)
Veale & Pearce (2009)	Observational	15 M	Australian rules football	Level 3	Gastrointestinal	4 friendly matches	WBGT: Day 1 = 33 – 33.9°C; Day 2 = 20.5 – 24.8°C Ambient temperature: Day 1 = 25 – 31.4°C; Day 2 = 20.1 – 26.8°C Relative humidity: Day 1 = 42 – 66%; Day 2 = 47 – 63.7°C	39°C (0.2)

RCT, randomised controlled trial; *NRCT,* non-randomised controlled trial; *M,* male; *F,* female; *WBGT,* wet bulb globe temperature; *IQR,* interquartile range.

CHARACTERISTICS OF THE PARTICIPANTS

Across all included studies, 350 participants (plus no reported participant numbers for two studies (Dancaster 1972; Goodman, Cohen & Walton 1985)) were recruited after accounting for shared data between studies (Girard et al. 2014; Girard, Racinais & Périard 2014; Knez & Périard 2014; Périard, Girard & Racinais 2014; Périard et al. 2014a, 2014b). Male-only participants were involved in 25 of the included studies (~81%), whilst only two studies included female-only participants (~6%). Three studies included a combination of female and male participants (~10%), and one study did not report the sex of their participants (~3%). There were no consistent classifications to describe the participant's level of competition among the included studies, so the five-level classification system defined by Russell et al. (2021) (adapted from De Pauw, Roelands, Cheung, et al. (2013) and Decroix et al. (2016)) was used. Classifications are:

- Level 1: Untrained or sedentary
- Level 2: Habitually active, physically fit and recreationally trained
- Level 3: Trained and competitive; high-level youth competition
- Level 4: Highly trained and competitive; semi-professional athletes
- Level 5: Professional; full-time paid athletes in professional competitive leagues

Using these defining criteria, eight studies examined level 5 participants (~26%), 12 studies examined level 4 participants (~39%), three studies examined level 3 participants (~10%), nine studies examined level 2 participants (~29%), and one study examined level 1 participants (~3%). One study did not report their participants level of competition. Three investigations included participants from a range of levels, and these studies have been included in counts for each level of participant examined within the study.

STUDY CHARACTERISTICS

Among the 31 included studies, 26 were observational, two were experimental (both randomised controlled trials), and three were quasi-experimental (two repeated measures designs and one non-randomised controlled trial). In-competition T_c has been reported in tennis (Elliott, Dawson & Pyke 1985; Girard et al. 2014; Girard, Racinais & Périard 2014; Hornery et al. 2007; Knez & Périard 2014; Morante & Brotherhood 2008a; Morante &

Brotherhood 2007; Morante & Brotherhood 2008b; Périard, Girard & Racinais 2014; Périard et al. 2014a, 2014b; Tippet et al. 2011), soccer (Diaw et al. 2014; Duffield et al. 2013; Edwards & Clark 2006; Mohr et al. 2004; Mohr et al. 2012; Ozgunen et al. 2010), rugby union (Cohen et al. 1981; Dancaster 1972; Goodman, Cohen & Walton 1985), Australian rules football (Aughey, Goodman & McKenna 2014; Duffield, Coutts & Quinn 2009; Veale & Pearce 2009), rugby sevens (Henderson et al. 2020; Taylor, Thornton, et al. 2019), squash (Blanksby et al. 1980), judo (Kouassi et al. 2019), handball (Delamarche et al. 1987), cricket (Stay et al. 2018), and basketball (Pliauga et al. 2015). Rectal measures of T_c were most common and used in 20 studies (~65%), whereas gastrointestinal methods were used in 12 studies (~39%; one study was forced to use a combination due to technical difficulties with their gastrointestinal devices and thus been counted in both). A comparison of the study designs, sports, and measurement types of the included studies is included in Figure 3.3.

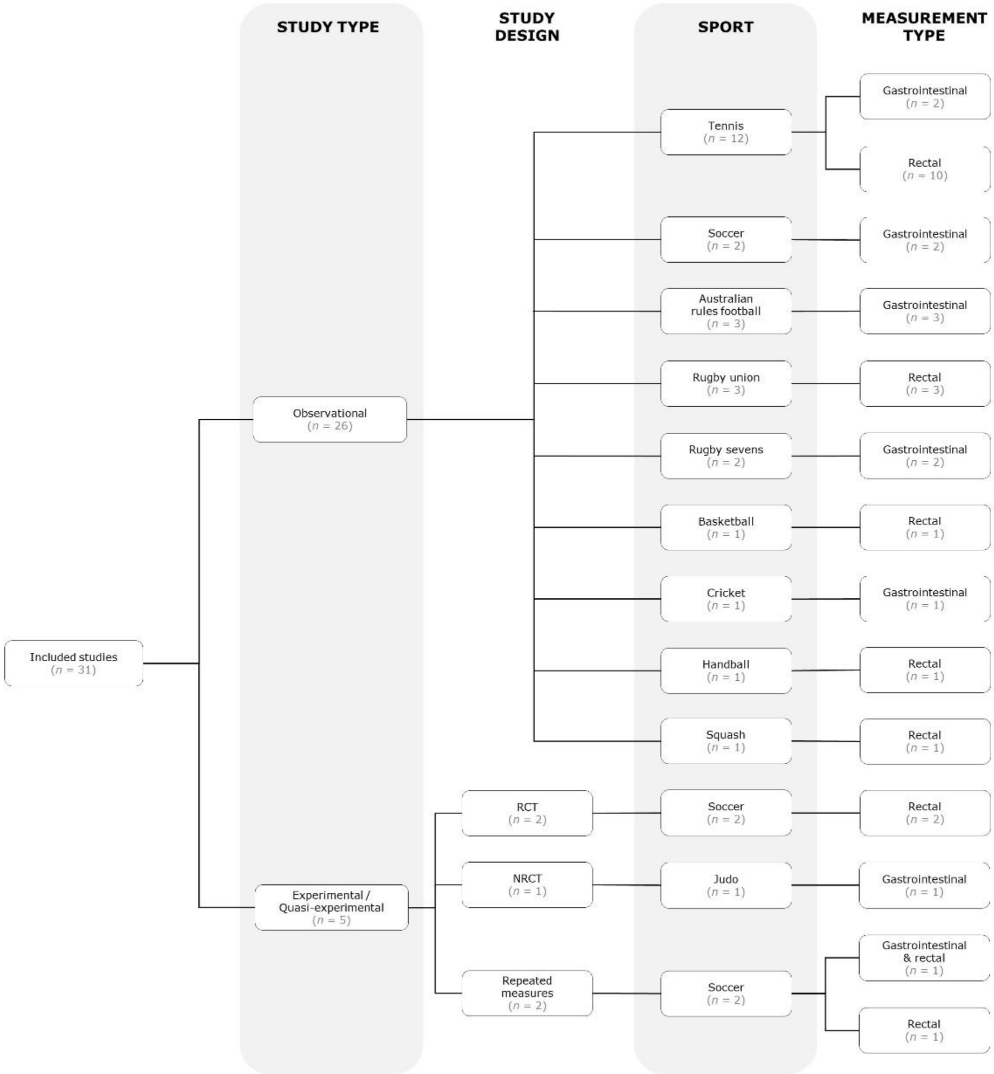
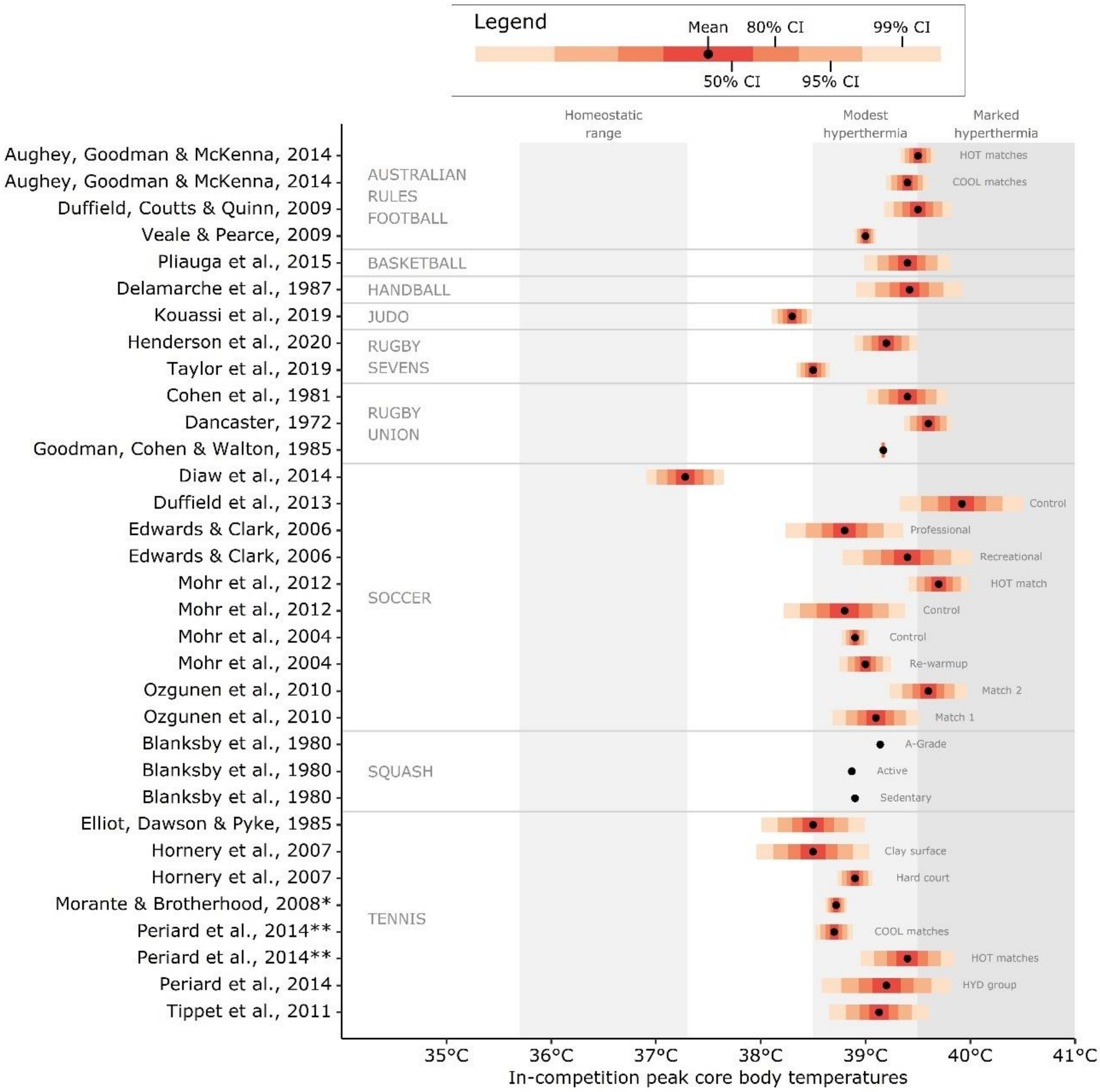


Figure 3.3 Flow diagram comparing the study types, designs, sports, and measurement types of the included studies. *RCT*: randomised controlled trial, *NRCT*: non-randomised controlled trial.

CORE BODY TEMPERATURE

Of the 31 studies included in this systematic review, three (~10%) found no evidence of hyperthermia (Diaw et al. 2014; Kouassi et al. 2019; Morante & Brotherhood 2008a), 22 (~71%) found evidence of 'modest' hyperthermia (between 38.5°C and 39.5°C (Nybo, Rasmussen & Sawka 2014)) (Blanksby et al. 1980; Cohen et al. 1981; Delamarche et al. 1987; Edwards & Clark 2006; Elliott, Dawson & Pyke 1985; Girard et al. 2014; Girard, Racinais & Périard 2014; Goodman, Cohen & Walton 1985; Henderson et al. 2020; Hornery et al. 2007; Knez & Périard 2014; Mohr et al. 2004; Morante & Brotherhood 2007; Morante & Brotherhood 2008b; Périard, Girard & Racinais 2014; Périard et al. 2014a, 2014b; Pliauga et al. 2015; Stay et al. 2018; Taylor, Thornton, et al. 2019; Tippet et al. 2011; Veale & Pearce 2009), and six (~19%) found evidence of 'marked' hyperthermia (39.5°C or greater (Nybo, Rasmussen & Sawka 2014)) (Aughey, Goodman & McKenna 2014; Dancaster 1972; Duffield et al. 2013; Duffield, Coutts & Quinn 2009; Mohr et al. 2012; Ozgunen et al. 2010) during intermittent sports competition (Figure 3.4). All 12 studies examining tennis athletes in competition found modest hyperthermia (Elliott, Dawson & Pyke 1985; Girard, Racinais & Périard 2014; Hornery et al. 2007; Knez & Périard 2014; Morante & Brotherhood 2008a; Morante & Brotherhood 2007; Morante & Brotherhood 2008b; Périard, Girard & Racinais 2014; Périard et al. 2014a, 2014b; Tippet et al. 2011). Three of the six investigations (50%) on soccer athletes during play detected marked hyperthermia (Duffield et al. 2013; Mohr et al. 2012; Ozgunen et al. 2010), and two detected modest hyperthermia (33%) (Edwards & Clark 2006; Mohr et al. 2004). Of the three studies conducted on Australian rules football athletes, two (~66%) found marked hyperthermia (Aughey, Goodman & McKenna 2014; Duffield, Coutts & Quinn 2009), and the other (~33%) found modest hyperthermia (Veale & Pearce 2009). One study in rugby union found marked hyperthermia (~33%) (Dancaster 1972), whilst the other two (~66%) rugby union (Cohen et al. 1981; Goodman, Cohen & Walton 1985) and both rugby sevens studies (Henderson et al. 2020; Taylor, Thornton, et al. 2019) found modest hyperthermia. In the single studies examining basketball (Pliauga et al. 2015), cricket (batters) (Stay et al. 2018), handball (Delamarche et al. 1987), and squash (Blanksby et al. 1980), each found modest hyperthermia on average during play. The studies where no hyperthermia was found were in cricket (fielders) (Stay et al. 2018), judo (Kouassi et al. 2019), and soccer (Diaw et al. 2014). The available WBGT values across all studies that found some degree of hyperthermia ranged from < 18°C (Aughey, Goodman & McKenna 2014) to 35.2°C (Périard et al. 2014a), and available exposure times (competition duration) ranged from a five minute judo bout (Kouassi et al. 2019) (not included in Figure 3.5 as environmental conditions weren't reported) to an 120 minute tennis match (Tippet et al. 2011) (Figure 3.5). The descriptive results of the included studies are presented in Table 3.1.



*Shared data across all 3 studies by Morante & Brotherhood (2007, 2008a, 2008b)
**Shared data across Periard et al. (2014a, 2014b, and 2014c), Girard et al. (2014), Girard, Racinais & Periard (2014), and Knez & Periard (2014)

Figure 3.4 Peak core body temperatures measured in competition during different intermittent sports. Black circles represent the group mean and the coloured bands beneath represent levels of confidence. Grey text to the right of the data provides context regarding the study group being represented, the number of observations, and environmental conditions during data collection. Grey-shaded areas represent the homeostatic (Obermeyer, Samra & Mullainathan 2017) and hyperthermic (Nybo, Rasmussen & Sawka 2014) ranges of core body temperature and are individually labelled above. Data shared across multiple studies are only represented once and indicated with an asterisk. Confidence intervals could not be constructed for the Blanksby et al. (Blanksby et al. 1980) data due to no measure of variability being reported, hence the mean value is presented alone. Data from Stay et al. (Stay et al. 2018) has been omitted from this figure as the authors reported non-parametric statistics. *CI*: confidence interval.

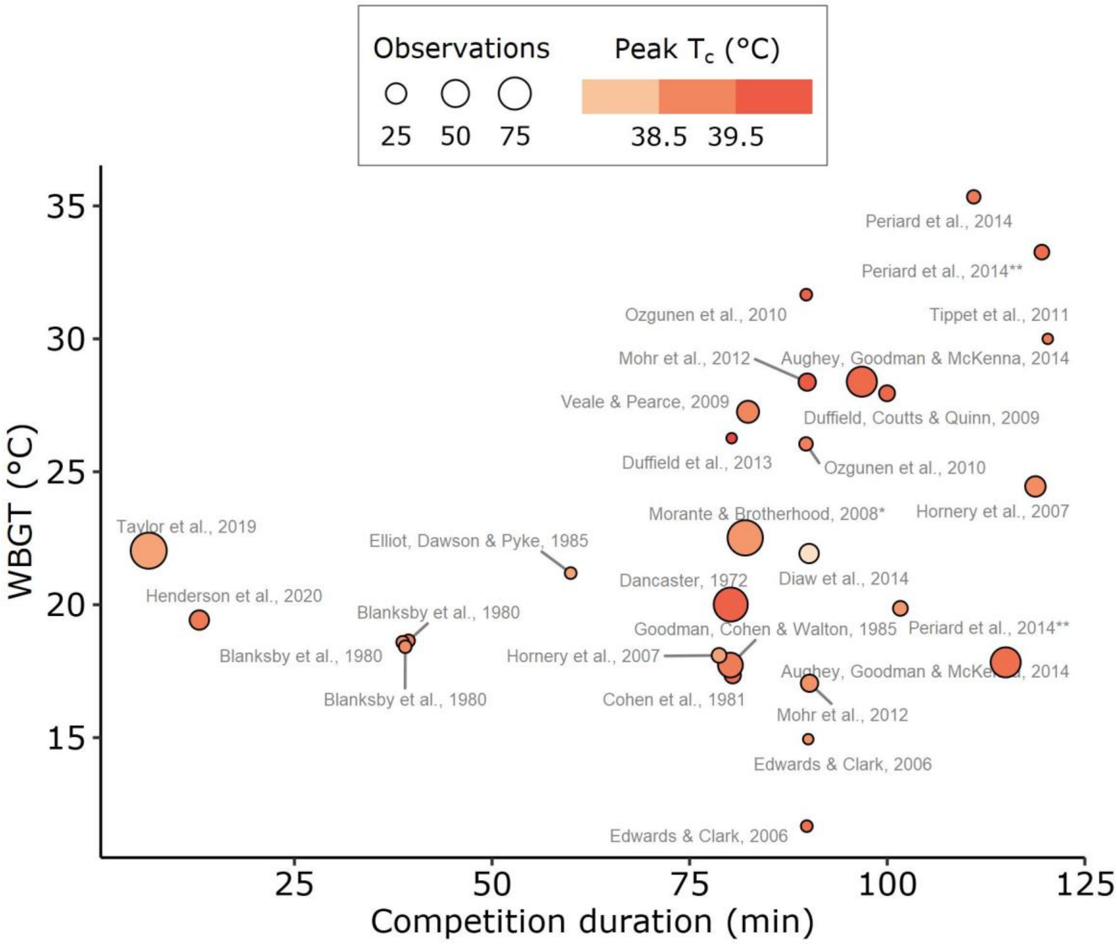


Figure 3.5 Relationship between competition duration, wet bulb globe temperature (WBGT), number of observations, and peak core body temperature (T_c). Where studies did not report WBGT, estimates based on the Liljegren method (Liljegren et al. 2008) were calculated. To uncover overlapping data points, a small amount of random variation to the location of each point was applied (known as jittering).

METHODOLOGICAL EVALUATION

The methodological evaluation results from the included studies are available in Table 3.2. The majority of included studies in this systematic review clearly described their study population (27/31 studies; ~87%) and adequately reported the environmental conditions during their data collection period (25/31 studies or ~81%; although increased reporting of WBGT, rather than ambient temperature and relative humidity, would facilitate more standardised comparison and more valid statistical models to be produced). Time spent in competition, and whether interchange players were used was reported in 22/31 studies (71%), potentially influencing group mean values when athletes with lower exposure durations are grouped with athletes completing a full match or bout. Of the 12 studies using gastrointestinal T_c measurements, 11 (92%) adequately reported the ingestion time before data collection (required to make assessments on the validity of the measurement (Byrne & Lim 2007)). When less than five hours had elapsed between gastrointestinal device ingestion and data collection, which was the case for six included studies, only three (50%) controlled for nutrition and hydration. None of the six investigations including female participants reported their menstrual cycle phase. Missing data was found in ten included studies, but only in seven (70%) of these was the missing data reported with appropriate justification provided. Very few studies included in this systematic review include continuous T_c monitoring over the data collection period (5/31 studies; ~16%), likely due to technology advancements only making this readily accessible in applied settings within the last decade. Similarly, the prevalence of reporting the results of tests and checks of normality before parametric statistical analysis is very low (4/31 studies; ~13%).

Table 3.2 Methodological evaluation checklist results.

Author/s	Clearly described population	Environmental information reported	Reported whether substitutes were used (including time spent in/out of competition)	Ingestion time prior to data collection reported (when gastrointestinal measurement used)	Control of nutrition consumption (if < 5 hours post-ingestion)	The menstrual cycle phase reported	Continuous data measurement	Reporting tests/ checks for normality of data	Missing data addressed and justified (if present)
Aughey, Goodman & McKenna (2014)	+	+	+	+	−	N/A	−	−	N/A
Blanksby et al. (1980)	+	−	+	N/A	N/A	N/A	−	−	N/A
Cohen et al. (1981)	+	+	−	N/A	N/A	N/A	−	−	+
Dancaster (1972)	−	+	−	N/A	N/A	N/A	−	−	N/A
Delamarche et al. (1987)	+	−	−	N/A	N/A	N/A	−	−	−
Diaw et al. (2014)	+	+	+	N/A	N/A	N/A	−	−	N/A
Duffield et al. (2013)	+	+	+	+	N/A	N/A	−	−	+
Duffield, Coutts & Quinn (2009)	+	+	−	+	N/A	N/A	−	−	−
Edwards & Clark (2006)	+	+	−	+	+	N/A	−	−	+
Elliott, Dawson & Pyke (1985)	+	+	+	N/A	N/A	N/A	−	−	N/A
Girard et al. (2014)	+	+	+	N/A	N/A	N/A	−	−	N/A
Girard, Racinais & Périard (2014)	+	+	+	N/A	N/A	N/A	−	−	N/A

Author/s	Clearly described population	Environmental information reported	Reported whether substitutes were used (including time spent in/out of competition)	Ingestion time prior to data collection reported (when gastrointestinal measurement used)	Control of nutrition consumption (if < 5 hours post-ingestion)	The menstrual cycle phase reported	Continuous data measurement	Reporting tests/ checks for normality of data	Missing data addressed and justified (if present)
Goodman, Cohen & Walton (1985)	+	+	−	N/A	N/A	N/A	−	−	+
Henderson et al. (2020)	+	+	+	+	N/A	−	+	+	N/A
Hornery et al. (2007)	+	+	+	+	−	N/A	−	+	N/A
Knez & Périard (2014)	+	+	+	N/A	N/A	N/A	−	−	N/A
Kouassi et al. (2019)	+	−	+	N/A	N/A	−	−	+	N/A
Mohr et al. (2004)	+	−	−	N/A	N/A	N/A	−	−	N/A
Mohr et al. (2012)	−	+	+	−	+	N/A	−	−	+
Morante & Brotherhood (2008a)	−	−	+	N/A	N/A	−	+	−	−
Morante & Brotherhood (2008b)	+	+	+	N/A	N/A	−	+	−	N/A
Morante & Brotherhood (2007)	+	+	+	N/A	N/A	−	+	−	N/A
Ozgunen et al. (2010)	+	+	−	+	+	N/A	−	−	+
Périard et al. (2014a)	+	+	+	N/A	N/A	N/A	−	−	N/A
Périard et al. (2014b)	+	+	+	N/A	N/A	N/A	−	−	N/A
Périard, Girard & Racinais (2014)	+	+	+	N/A	N/A	N/A	−	−	N/A

Author/s	Clearly described population	Environmental information reported	Reported whether substitutes were used (including time spent in/out of competition)	Ingestion time prior to data collection reported (when gastrointestinal measurement used)	Control of nutrition consumption (if < 5 hours post-ingestion)	The menstrual cycle phase reported	Continuous data measurement	Reporting tests/ checks for normality of data	Missing data addressed and justified (if present)
Pliauga et al. (2015)	+	−	+	N/A	N/A	N/A	−	−	N/A
Stay et al. (2018)	−	+	+	+	−	N/A	−	+	N/A
Taylor, Thornton, et al. (2019)	+	+	−	+	N/A	N/A	+	−	+
Tippet et al. (2011)	+	+	+	+	N/A	−	−	−	N/A
Veale & Pearce (2009)	+	+	+	+	N/A	N/A	−	−	N/A

DISCUSSION

SUMMARY OF MAIN RESULTS

This systematic review aimed to synthesise the research findings regarding the T_c responses to intermittent sports competition in the field. The majority of included studies identified magnitudes of T_c that have been associated with hyperthermia (and related performance and health effects) (Nybo, Rasmussen & Sawka 2014) occurring during intermittent sports competition across sports, competition levels, sexes, exposure times, and environmental conditions. Our findings show that athletes, coaches, practitioners, and/or policymakers are in many cases justified to seek methods that may limit the heat strain experienced by athletes competing in intermittent sports such as heat acclimatisation/acclimation training interventions (Racinais, Alonso, et al. 2015) and mixed method cooling in and around competition (Taylor, Carter & Stellingwerff 2020). However, there is variation in peak T_c among the studies included in this review, likely resulting from a complex interplay between the physical intensity and duration of the sport, environmental conditions during competition, methods of measurement, and athlete genetics (modulated by the magnitude of heat acclimation/acclimatisation). More detailed reporting of contextual data, as well as greater standardisation in reporting is necessary to gain a higher resolution understanding of the relationships between these factors and peak T_c through meta-analytic statistical methods such as meta-regression. This would allow stronger inferences to be drawn; and athletes, coaches, practitioners, and policymakers would be able to intervene more confidently to improve the performance and/or health of competing athletes (and minimising the likelihood of intervening negatively or unnecessarily).

METHODOLOGICAL CONSIDERATIONS

Whilst the findings of the present review provide an important synthesis of the available data collected from intermittent sport athletes, we anticipated (based on prior scoping research and expert consultation) that given the heterogeneity of the methods within the included studies, summary estimates and moderators could not be calculated. Nonetheless, the combined results show a common presence of hyperthermia (Figure 3.4) of magnitudes shown to impair performance (Nybo, Rasmussen & Sawka 2014). The majority of included studies reported either WBGT or ambient temperature and relative humidity, the exposure time in competition, and clearly described their population (particularly the studies from 2010 onwards; ~55% or 17/31 of included studies). These parameters (environmental conditions, exposure dose, and population) are arguably the most important contributors to the heat strain experienced by competing intermittent sport athletes, and an improved understanding of the relationships between these factors and their effect on T_c (through statistical modelling techniques) will facilitate improved anticipation of future potential heat strain. This would enable athlete support staff and policymakers to refine the interventions or plans they may have in place to maximise competition performance and safety with greater precision. A further improvement in the methodological quality that is becoming more prevalent in the research is the use of T_c measurement technology capable of continuous data monitoring (as opposed to capturing data at discrete time points during breaks in play as was done previously). This allows a more valid assessment of peak T_c, as the peak is likely to occur during play after prolonged, intense, and metabolically demanding actions. Although this technology is not new (i.e., a sampling frequency of 60 s was used in earlier studies by Morante & Brotherhood in 2007 – 2008 (Morante & Brotherhood 2008a; Morante & Brotherhood 2007; Morante & Brotherhood 2008b), albeit measured rectally whereas gastrointestinal is now more common), improvements in technology and decreased cost in recent years has made acquiring such devices much more feasible for researchers and practitioners. Overall, the volume of literature/studies surfaced from this systematic search and their combined results (interpreted within the context of methodological quality), indicate that the relationship between intermittent sports competition and high T_c is trustworthy, although the independent effects of WBGT and exposure dose require further research and analysis before explanatory models with summary estimates and moderators can be developed.

LIMITATIONS AND POTENTIAL BIASES IN THE REVIEW PROCESS

The primary limitation of the present review is the heterogeneity between studies preventing the combined data from being meta-analysed. More research is needed between sports (and associated competition durations), in different environmental conditions, and levels of competition to attain sufficient homogeneity within groups for appropriate statistical synthesis. Further limitations include the consideration of only T_c in the present review despite performance decrements being observed from other thermal strain factors such as T_{sk} (Ely et al. 2009) and the lack of performance outcomes reported. A current gap in the body of evidence presented is the relatively low volume of research on athletes competing at the highest levels of intermittent sport (level 5 based on Russell et al. (2021) classification system; 8/31 included studies or ~26%) where small changes are considered important and the implications on performance are of greatest consequence. Without sufficient statistical power being reached from a larger volume of relevant data collected from this population, the small but practically important changes in the physiology and performance of athletes at this level (Hopkins, Hawley & Burke 1999) will remain undetected during quantitative synthesis. Opportunities for performance enhancement through practical and effective interventions for intermittent sport athletes to better handle thermally challenging conditions may therefore be missed, with potential implications on competitive outcomes and associated financial costs (Di Simone & Zanardi 2021). A potential bias in the body of evidence presented in this review lies in the volume of data reported across multiple studies. Whilst different hypotheses and distinct methodologies are presented across these studies, there remains the potential for researchers to mistake the data within these studies as distinct (as it is often not explicitly stated), generating duplicate data points when performing literary or quantitative synthesis and more heavily weighting the findings toward the characteristics of this data.

IMPLICATIONS FOR PRACTICE AND FUTURE RESEARCH

The studies included in this systematic review contain data with high external validity as they were collected in competition (competitive, friendly, or experimental) with real external influencing factors (e.g., unpredictable opponents/defenders, specific technical skill execution, tactical decision-making, match/competition physical demands). Whilst this allows the findings to be highly generalisable, it comes at the expense of the high degree of experimental control possible in laboratory studies that can test hypotheses whilst tightly controlling for many of the external factors present in the real world. The best original research evidence comes from controlled trials where changes in a dependent variable are observed when altering one or many independent variables, but for transferability to occur from scientific research into practice, research from the field is required (Slattery, Crowcroft & Coutts 2021). This enables researchers and practitioners to build upon the knowledge gained from controlled studies by practically applying the theory more broadly to determine efficacy and feasibility in the real world. Whilst this systematic review is the first investigating heat strain in competition on intermittent sport athletes, prior probability based on the substantial volume of research findings from endurance sports in similar environmental conditions, combined with the preliminary results in the current review, suggest that exercise-induced hyperthermia frequently occurs in intermittent sport athletes during competition. With the known performance and health effects observed from these magnitudes of hyperthermia, future research should look to investigate feasible practice-focused interventions for these athletes. Strong scientific and applied support exists for heat acclimation/acclimatisation training interventions (Tyler et al. 2016) and acute cooling interventions (Tyler, Sunderland & Cheung 2015) based on research and practice from endurance athletes and practitioners. More research investigating the efficacy and practicality of these methods in intermittent sport athletes and settings is required before these findings can be universally considered best-practice management of high thermal strain during competition across all sports.

CONCLUSION

This systematic review has synthesised the available thermal strain data collected in competition from intermittent sport athletes. Almost 90% of the studies that met the eligibility criteria found some degree of hyperthermia (T_c > 38.5°C), with almost 20% of the studies finding ‘marked’ hyperthermia (T_c >39.5°C). Exercise-induced hyperthermia has been associated with a range of negative performance and health outcomes in athletes. Practitioners and coaches supporting intermittent sport athletes are justified to seek interventions aimed at mitigating the high heat strain observed in competition. More research is required to determine the most effective interventions for this population that are practically viable in intermittent sports settings (that are often constrained by many competing demands). Greater statistical power and homogeneity among studies are required to quantify the independent effects of WBGT, competition duration, sport, and level of competition on peak T_c, all likely to be key modulators of the thermal strain experienced by competing athletes.

CHAPTER 4 | CORE TEMPERATURE CHANGES DURING AN ELITE FEMALE RUGBY SEVENS TOURNAMENT

Henderson, M.J., Chrismas, B.C.R., Stevens, C.J., Coutts, A.J. & Taylor, L. (2020). Core temperature changes during an elite female rugby sevens tournament. *International Journal of Sports Physiology and Performance*, 15(4), 571 – 580.

ABSTRACT

Purpose: Characterise player T_c across a WRWSS tournament day and determine the efficacy of commonly employed cold water immersion (CWI) protocols. **Methods:** T_c was measured in twelve elite female rugby sevens athletes across 3 games (G1 – 3) from day 1 of the Sydney WRWSS tournament. Exertional heat illness symptoms, perceptual scales, CWI details, playing minutes, external load data (measured by Global Positioning Systems) and wet bulb globe temperature (range: 18.5 – 20.1°C) were also collected. Linear mixed models and magnitude-based inferences were used to assess differences in T_c between periods [G1 – 3 and warm-ups (WU)]. **Results:** Average T_c was *very likely* lower (ES ± 90% CL, -0.33 ± 0.18) in G1 compared to G2. Peak T_c was *very likely* (0.71 ± 0.28) associated with increased playing time. CWI did not remove the accumulated T_c due to WU and match-play activity (~1 – 2°C rise in T_c still present compared to T_c at WU onset for players ≥ 6 min match-play). **Conclusions:** Elite female WRWSS athletes experienced high T_c during WU (T_c peak 37.9 – 39.0°C) and matches (T_c peak 37.9 – 39.8°C), a magnitude known to reduce intermittent high-intensity physical performance (≥39°C). The CWI protocol resulted in players (≥ 6 min match-play) with a ~1 – 2°C raised T_c compared to T_c at WU onset.

INTRODUCTION

Rugby sevens is a modified shortened version of 15-a-side rugby union, where teams play with 7 players (5 reserves), across 7-minute halves, on a full-sized rugby union pitch. The WRWSS is the premier international rugby sevens series/competition, with 8 tournaments per season. Tournaments are competed over 2 – 3-day periods, with up to 3 matches per day and ~3 hours between matches. WRWSS match-play is characterised by frequent bouts of high-intensity activity and collisions (Ross, Gill & Cronin 2015), with speeds reported as 85.8 ± 3.9 $m \cdot min^{-1}$ with 11 ± 2.7% performed above 5 $m \cdot s^{-1}$ (Clarke, Anson & Pyne 2017).

The WRWSS tournaments are contested in the southern and northern hemispheres resulting in variable environmental match-day conditions, where teams may travel from their domestic winter months to compete in summer months elsewhere, often facing extremes of heat and/or humidity. Match-play data from the male equivalent [reporting higher physical match intensities (Clarke, Anson & Pyne 2017)] of the WRWSS within temperate [13.8 – 22.3 wet bulb globe temperature (WBGT); London 2017] and warm (21.4 – 27.0 WBGT; Singapore 2017) WBGT environments, has demonstrated high T_c [peak of 39.9°C and 39.6°C in temperate and warm conditions, respectively (Taylor, Thornton, et al. 2019)]. This presents a challenge to practitioners and players, as a $T_c \geq$ 39°C can impair intermittent/repeated sprint-based performance through (i) reductions in arterial oxygen delivery to the working muscles, (ii) greater reliance on anaerobic energy provision and (iii) accelerated accumulation of H^+ (Girard, Brocherie & Bishop 2015).

Physical and physiological differences in thermoregulation exist between sexes (e.g., greater subcutaneous fat content, a larger ratio of body surface to body mass, and smaller sweat response to heat load in females) (Kaciuba-Uscilko & Grucza 2001). Coupling this with the known anthropometrics of elite rugby sevens athletes [e.g., females are shorter, and lighter with a higher fat content (Clarke, Anson & Pyne 2017)], female players may be more susceptible to rapid rises in $T_c \geq 39°C$ and subsequent performance decrements (Girard, Brocherie & Bishop 2015) for the same work produced. Considering the high T_c from temperate/warm match-play in males (Taylor, Thornton, et al. 2019) capable of reducing physical performance (Girard, Brocherie & Bishop 2015), other hotter tournaments of the WRWSS and Tokyo 2020/1 [expected to be the hottest modern Olympics to date (~30°C, with relative humidity exceeding 75% (Kakamu et al. 2017; Kashimura, Minami & Hoshi 2016))] may challenge practitioners to manage player body temperatures to achieve optimal performance. This may be of greater importance for female athletes given the performance variation observed across the menstrual cycle in hot, humid conditions (Janse et al. 2012).

Cold water immersion (CWI) is a commonly used acute post-game (N.B several games within WRWSS tournament day) recovery tool for rugby sevens athletes, proposed to control hyperthermia, reduce muscle inflammation and damage, and decrease muscle soreness (Ihsan, Watson & Abbiss 2016). However, the efficacy of rugby sevens-specific CWI protocols (Schuster et al. 2018), within a real-world elite tournament scenario, is not available [e.g., total heat storage as a consequence of each match plus associated warm-up (WU), and whether the CWI protocol removes this]. Telemetric capsules could wirelessly, and relatively non-invasively (Bongers et al. 2018), acquire this within a WRWSS tournament day for T_c characterisation and CWI efficacy data.

This study aims to characterise (1) T_c values for elite female athletes within and between matches of a WRWSS tournament day, and (2) the efficacy of post-game CWI protocols. It is hypothesised that (i) WRWSS matchplay will result in T_c values ≥ 39°C and (ii) the commonly employed post-game CWI protocol will not entirely remove body heat gained from the WU and match-play.

METHODS

SUBJECTS

Data were collected from a total of twelve seasonally heat-acclimatised female athletes (see Table 4.1 for details) from a single 2018-19 WRWSS team based in Sydney, Australia, across one tournament day. Written informed consent was provided, under ethical approval from the Southern Cross University Human Research Ethics Committee (ECN-18-216) in the spirit of the Helsinki Declaration.

Table 4.1 Player characteristics, anthropometry, and body composition. Data are presented as median (minimum – maximum).

Age (y)	23 (17 – 30)
Height (m)	1.69 (1.65 – 1.74)
Body mass (kg)	67.9 (60.0 – 79.5)
Sum SF (mm)	63.3 (40.7 – 78.1)
Triceps SF (mm)	6.9 (3.6 – 8.7)
Subscapular SF (mm)	8.5 (5.6 – 14.8)
Bicep SF (mm)	4.0 (2.5 – 5.8)
Supraspinale SF (mm)	7.9 (4.5 – 15.0)
Abdomen SF (mm)	11.2 (4.1 – 17.0)
Thigh SF (mm)	15.9 (8.5 – 21.6)
Calf SF (mm)	7.4 (3.0 – 9.5)
Body fat (%)	19.2 (12.6 – 26)
LBM (kg)	54.7 (49.8 – 66.6)

SF = skinfold; LBM = lean body mass

DESIGN

Data were collected across the first day (three games played, two wins, one loss) of the Australian WRWSS tournament in Sydney, Australia (February 1 – 3, 2019). Players had been in the same time zone ≥ 14 days prior to the tournament; thus, the circadian misalignment was not a confounding influence. In line with elite team sport practice, menstrual cycle could not be controlled. Only nutritional supplements such as protein powder and carbohydrate liquids/gels were consumed by athletes during the study period.

METHODOLOGY

Players ingested an e-Celsius™ telemetric capsule (BodyCap, Caen, France) the night prior to the tournament, and another upon waking on the first match day. T_c data was only included within the statistical model when ≥ 5 hours had elapsed post-ingestion, a criterion used previously to ensure the capsule was in the lower intestine (Byrne & Lim 2007; Taylor, Stevens, et al. 2019; Taylor, Thornton, et al. 2019). T_c was sampled at 30 s intervals, with data downloaded at the end of the day via a wireless data receiver (e-Viewer, BodyCap, Caen, France). Capsules were set-up, calibrated, and handled as extensively outlined elsewhere (Taylor, Stevens, et al. 2019; Taylor, Thornton, et al. 2019; Travers et al. 2016). The e-Celsius™ system has been shown valid and reliable for intermittent-running exercise (Travers et al. 2016), has excellent validity (ICC 1.00), test-retest reliability (ICC 1.00) and inertia in water bath experiments between 36°C and 44°C (Bongers et al. 2018), and has been used previously within elite rugby sevens matches (Taylor, Thornton, et al. 2019).

Playing minutes for individual athletes for each game were collected by the team's sports scientist. Specific pre-defined periods relative to T_c were employed within analyses (specific timings provided in Table 4.2):

- *Baseline (BL)*: 60 minutes prior to prime.
- *Activation / Primer:* Time spent completing pre-warm up movement.
- *Warm-up*: Time spent with the team undertaking team warm-up.
- *Game*: Time spent in the game.
- *CWI*: Time spent submerged in cold water following the match.

Signs and symptoms of exertional heat illnesses (EHI) were collected following each game immediately prior to the CWI protocol, using a modified survey instrument (Périard et al. 2017). Specifically, the athletes were asked in a yes/no manner if they had experienced (i) cramping; (ii) vomiting; (iii) nausea; (iv) severe headache; (v) collapsing/fainting; or (vi) any other symptom that might relate to heat illness (Périard et al. 2017). CWI was provided for teams by the local organisers, with submersion time of day (see Table 4.2) and duration (see results section) recorded (water temperature range: 6.1 – 7.3°C). Players were submerged to hip height for the duration of their CWI intervention. No other post-game cooling intervention methods were used.

WBGT (SD-2010, Reed Instruments, NC, USA) was obtained immediately prior to, during and post-WU (in the WU area outside of the stadium) and matches (5 m from the sideline). WBGT values obtained within each pre-defined period were averaged and are presented in Table 4.2. The day prior to the tournament within the stadium WBGT peak was 37.5°C, with expectations that tournament day one would see similar WBGT values, however, conditions on the day were surprisingly mild (≤ 20°C WBGT; see Table 4.2).

Table 4.2 Core body temperature, wet-bulb globe temperature, and local time of day across each specific period of day 1 of the Sydney tournament. Data are presented as median (minimum – maximum) for all players. Match-play data is also presented for players who had ≥ 6 min match-play only [game 1 (n = 6), game 2 (n = 7), game 3 (n = 9)].

Period	T_c peak (˚C)	T_c min (˚C)	T_c average (˚C)	ΔT_c period (˚C)	ΔT_c BL (˚C)	Combined Δ(˚C)	ΔΔCWI(˚C)	WBGT (˚C)	Time
BL	37.5 (37.2 – 37.7)	37.0 (36.7 – 37.3)	37.3 (37.0 – 37.5)						
Prime	38.5 (38.1 – 38.8)	37.4 (37.1 – 37.9)	38.0 (37.5 – 38.2)	1.1 (0.6 – 1.5)	1.2 (0.8 – 1.5)				12:16 – 12:36
WU 1	38.5 (37.9 – 39.0)	37.8 (36.9 – 38.1)	38.2 (37.4 – 38.5)	0.9 (0.4 – 1.2)	1.3 (0.6 – 1.9)			18.8 – 20.1	13:14 – 13:39
Game 1	38.8 (37.9 – 39.7)	38.1 (37.0 – 38.6)	38.4 (37.7 – 39.1)	0.9 (0.4 – 2.0)	1.8 (0.7 – 2.4)	1.3 (0.5 – 2.7)		19 – 19.6	13:51 – 14:11
>6 min	*39.6 (38.6 – 39.7)*	*38.3 (37.6 – 38.6)*	*39.0 (38.4 – 39.1)*	*1.2 (0.4 – 2.0)*	*2.3 (1.2 – 2.4)*	*1.7 (0.6 – 2.7)*			
CWI 1	38.4 (37.8 – 39.3)	37.5 (37.0 – 38.0)	37.9 (37.5 – 38.4)	0.8 (0.4 – 1.8)	1.2 (0.5 – 1.9)		0.2 (-1.1 – 2.0)	6.1	14:25 – 14:44
WU 2	38.6 (38.2 – 39.0)	37.6 (37.0 – 38.1)	38.2 (37.7 – 38.6)	1.0 (0.8 – 1.4)	1.3 (0.9 – 1.9)			19.2 – 19.6	16:00 – 16:20
Game 2	39.0 (38.2 – 39.8)	38.4 (37.4 – 38.7)	38.7 (37.9 – 39.3)	0.7 (0.2 – 1.2)	1.8 (0.9 – 2.5)	1.3 (0.8 – 2.4)		18.9 – 20.0	16:38 – 16:55
>6 min	*39.1 (38.2 – 39.8)*	*38.4 (37.4 – 38.7)*	*38.9 (37.9 – 39.3)*	*0.7 (0.5 – 1.2)*	*1.9 (0.9 – 2.5)*	*1.3 (1.0 – 2.4)*			
CWI 2	38.4 (37.5 – 39.1)	37.8 (37.0 – 38.2)	38.1 (37.3 – 38.4)	0.5 (0.2 – 1.0)	1.2 (0.3 – 1.7)		0.8 (-0.1 – 1.9)	7.3	17:16 – 17:32
WU 3	38.6 (38.1 – 38.9)	37.5 (37.0 – 38.0)	38.1 (37.6 – 38.4)	1.1 (0.6 – 1.8)	1.4 (0.8 – 1.9)			18.5 – 18.8	18:22 – 18:42
Game 3	39.0 (38.4 – 39.6)	38.3 (37.9 – 38.5)	38.6 (38.2 – 39.6)	0.6 (0.3 – 1.3)	1.8 (1.1 – 2.3)	1.6 (1.0 – 2.2)		18.9 – 20.1	18:56 – 19:17
>6 min	*39.3 (38.4 – 39.6)*	*38.4 (37.9 – 38.5)*	*38.9 (38.2 – 39.0)*	*0.8 (0.3 – 1.3)*	*2.0 (1.1 – 2.3)*	*1.6 (1.1 – 2.2)*			
CWI 3	38.0 (37.8 – 38.6)	37.7 (37.2 – 38.0)	37.9 (37.7– 38.2)	0.4 (0.3 – 0.7)	0.8 (0.6 – 1.2)		1.2 (0.7 – 1.6)	6.6	19:50 – 20:06

BL = baseline; WU = warm-up; CWI = cold water immersion; T_c = core temperature; WBGT = wet bulb globe temperature

Activity profiles during matches were measured using 10 Hz GPS devices (EVO, GPSports, Canberra, Australia). These have shown good inter-unit reliability for distance (m) (CV: 0.2 ± 1.5%), average speed ($m \cdot min^{-1}$) (CV: 0.2 ± 1.5%), max velocity ($m \cdot s^{-1}$) (CV: 0.2 ± 1.5%), high-speed running (distance covered >5 $m \cdot s^{-1}$) (CV: 0.5 ± 1.5%), and average acceleration/deceleration ($m \cdot s^{-2}$) (CV: 1.2 ± 1.5%) (Thornton et al. 2019). Each unit was assigned to an individual player and worn in a small pouch in their match jersey, positioning the unit between the scapula blades of the player. Following each match, devices were downloaded using the manufacturer's proprietary software (GPSports Console, GPSports, Canberra, Australia). Metrics exported from the GPS data included match duration (min), average speed ($m \cdot min^{-1}$), high-speed running per minute ($HSR \cdot min^{-1}$; average distance covered at >5 $m \cdot s^{-1}$ per minute), very high-speed running per minute ($VHSR \cdot min^{-1}$; average distance covered at >6 $m \cdot s^{-1}$ per minute), and average acceleration/deceleration (Ave Acc/Dec; $m \cdot s^{-2}$).

Thermal sensation (TS) was measured using a 17-point category ratio scale (where 0 = 'unbearably cold' and 8 = 'unbearably hot') (Young et al. 1987). Thermal comfort (TC) was measured using a 10-point category ratio scale (where 1 = 'comfortable' and 10 = +1 above 'extremely uncomfortable') (Borg 1982). Rating of perceived exertion (RPE) was measured using the CR-10 category ratio scale (where 0 = rest and 10 = maximal) (Borg 1982).

The TS, TC, RPE (all post-game), T_c and GPS measures were obtained as per Figure 4.1, by the same practitioner using standardised language and procedures.

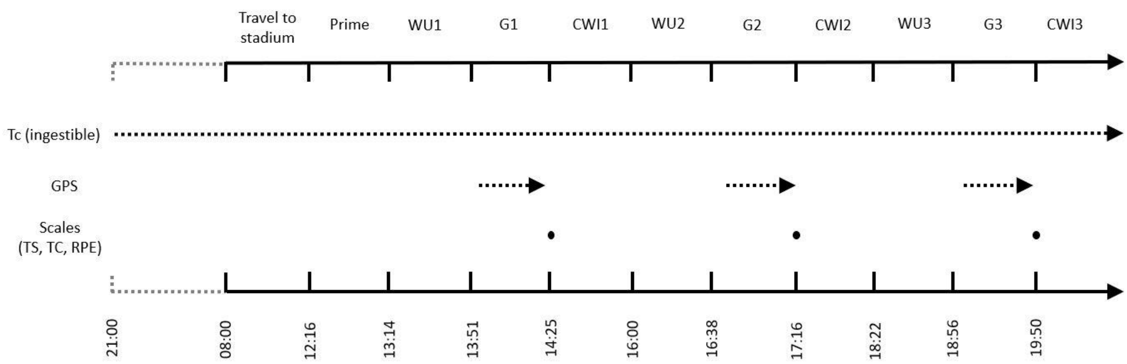


Figure 4.1 Experimental schematic. Tc = core temperature (ingestible telemetric pill); GPS = Global Positioning Systems; TS = thermal sensation; TC = thermal comfort; RPE = rating of perceived exertion; CWI = cold water immersion; WU = warm-up.

STATISTICAL ANALYSES

Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 25 (IBM, SPSS Inc, Chicago, IL, USA), and magnitude-based inferences (MBIs) customisable spreadsheets, using the raw data (Hopkins et al. 2009). Initially, descriptive statistics were generated, and normality was checked using quantile-quantile (Q-Q) plots (Grafen & Hails 2002). Descriptive statistics are reported as median and range (min – max) unless otherwise stated. GraphPad Prism 8 (GraphPad Software, CA, USA) was used to create Figures 4.2 – 4.4. Individual player T_c was determined and averaged for each pre-defined period, with peak T_c values for each period also extracted. At each period the individual player change (delta; Δ) within period, and relative to baseline (BL) were calculated. Additionally, minimum T_c values from each WU (WU 1, WU 2, WU 3) were subtracted from peak T_c values from each game (G1 – 3), to calculate total heat gained across each WU and game pair (ΔT_c combined). To examine the effectiveness of CWI in removing the total heat gained in ΔTc combined, the ΔT_c combined value was subtracted from the ΔCWI, providing a ΔΔCWI value.

Linear mixed models (LMM) were used to determine differences in: (i) T_c (peak, average, Δ period, Δ BL, Δ combined) across all periods, and between WU and games; (ii) RPE, TS, TC, minutes played, and all external load (GPS) variables between games; and (iii) ΔΔCWI between each period (i.e., CWI 1, CWI 2, CWI 3). Specifically, fixed (i.e., period) and random (i.e., participant) effects for the LMM were fit for each dependent variable (West, Welch & Galecki 2014), and a nested effect design was used, where the player was nested in the period. This design estimates mean differences in individual T_c, and also models the between-player variability in T_c within each period. The most appropriate model was chosen using the smallest Hurvich and Tsai criterion (AIC) (Hurvich & Tsai 1995) following the principle of parsimony. The least squares mean test provided pairwise comparisons between the fixed effects. Raw differences are reported as mean (95% confidence intervals). Normality and homogeneity of variance of the residuals were checked using Q-Q plots, and scatter plots respectively, and deemed plausible in each instance. Furthermore, the relationship between minutes played and all external load (GPS) variables on peak T_c was assessed using LMM (random coefficient model). Peak T_c for all three games was included in the model as a dependent variable (outcome), and minutes played and all external load (GPS) variables (all three games combined) were separately entered as fixed effects (predictors). Using a random intercept and slope design, player identification was nested within the predictors. All analyses were initially performed with all players, and subsequently with players who had ≥ 6 min (~40% of game time) match-play per game only. Perceptual and external load (GPS) data were modelled only for those players with ≥ 6 min match-play per game. Cohen's *d* effect sizes (ES), and 90% confidence limits (CLs) were obtained using the MBI spreadsheets and categorised using standardised thresholds of; < 0.2 trivial, 0.21 – 0.60 small, 0.61 – 1.20 moderate, 1.21 – 2.0 large, and > 2.0 very large (Hopkins et al. 2009) only when the LMM results showed a significant *p*-value (significance was accepted as $p \leq 0.05$). Differences were considered real if there was a >75% likelihood of the observed effect exceeding the smallest worthwhile effect (0.20 x between subject SD), using the following qualitative descriptions; 75 – 95% *likely*, 95 – 99.5% *very likely*, and > 99.5% *most likely* (Hopkins et al. 2009). Data is reported as ES ± 90% CI.

RESULTS

Raw data for T_c for all players, and perceptual and GPS data for players who had ≥ 6 min match-play are presented in Tables 4.2 and 4.3, respectively.

Table 4.3 Match-play minutes, rate of perceived exertion, thermal sensation, thermal comfort, and external load variables across the three games of day 1 of the Sydney tournament. Data are presented as median (minimum – maximum) for players who had ≥ 6 min match-play only [game 1 (n = 6), game 2 (n = 7), game 3 (n = 9)].

Measure	**Game 1**	**Game 2**	**Game 3**
Minutes played (min)	15.1 (8.5 – 16.5)	11.1 (8.9 – 14.6)	11.4 (6.1 – 17.3)
RPE	7 (5 – 8)	6 (3 – 8)	5 (3 – 8)
TS	5 (2.5 – 5.5)	5.5 (3 – 6)	4 (3 – 5)
TC	3 (1 – 4)	3 (1 – 4)	2 (1 – 2) ***†††
Avg speed ($m \cdot min^{-1}$)	99.2 (92.9 – 102.9)	99.3 (96.3 – 114.0)	91.0 (80.6 – 104.0)
$HSR \cdot min^{-1}$	14.4 (8.9 – 18.6)	19.4 (12.9 – 30.3)	8.1 (6.1 – 15.4)
$VHSR \cdot min^{-1}$	5.1 (0.3 – 9.4)	8.3 (2.4 – 19.8)	3.9 (0 – 8.8)
Ave acc/dec ($m \cdot s^{-2}$)	0.55 (0.53 – 0.58)	0.51 (0.46 – 0.55)	0.55 (0.51 – 0.57)

Avg = average; RPE = rate of perceived exertion; TS = thermal sensation; TC = thermal comfort; HSR = high-speed running; VHSR = very high-speed running, Ave acc/dec = average acceleration/deceleration. The likelihood of the observed effect exceeding the smallest worthwhile change (0.2 x between subject SD) when compared to game 1 are denoted as; *** = most likely. When compared to game 2 differences are expressed as; ††† = most likely.

Core temperature across all periods: Peak T_c was ≥ 39°C for five players in game 1, and six players in games 2 and 3 (Figure 4.2). Peak and average T_c, when compared to BL, was higher throughout all periods for all players ($p < 0.001$; $p < 0.001$ respectively) and in those who had ≥ 6 min match-play ($p < 0.001$; $p < 0.001$, respectively). Differences are reported in Table 4.4 and Figure 4.2.

Table 4.4 Differences in core body temperature for each period compared to baseline. Data are presented as mean (95% CI) for all players and for players who had ≥ 6 min match-play only [game 1 (n = 6), game 2 (n = 7), game 3 (n = 9)]. Only significant data is shown.

Period	**Prime**	**WU 1**	**Game 1**	**CWI 1**	**WU 2**	**Game 2**	**CWI 2**	**WU 3**	**Game 3**	**CWI 3**
BL										
T_c peak (°C)										
Mean diff	0.75 (0.46 to 1.04) ***	0.76 (0.45 to 1.07) ***	1.14 (0.73 to 1.54) ***	0.73 (0.38 to 1.08) ***	0.89 (0.58 to 1.20) ***	1.24 (0.92 to 1.56) ***	0.68 (0.36 to 1.00) ***	0.88 (0.57 to 1.18) ***	1.22 (0.88 to 1.56) ***	0.52 (0.17 to 0.86) ***
ES	5.8 ± 2.3	5.7 ± 2.3	8.7 ± 3.5	5.5 ± 2.2	6.8 ± 2.7	8.8 ± 3.6	4.9 ± 2.0	6.6 ± 2.7	9.3 ± 3.7	3.7 ± 2.0
p-value	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.008$
T_c avg (°C)										
Mean diff	0.56 (0.19 to 0.94) ***	0.58 (0.20 to 0.96) ***	0.95 (0.57 to 1.33) ***	0.57 (0.09 to 0.85) **	0.74 (0.36 to 1.12) ***	1.17 (0.79 to 1.55) ***	0.58 (0.20 to 0.96) ***	0.71 (0.32 to 1.09) ***	1.09 (0.71 to 1.48) ***	0.52 (0.14 to 0.90) ***
ES	4.7 ± 2.3	5.0 ± 2.4	8.1 ± 3.3	2.2 ± 1.5	6.3 ± 2.5	9.3 ± 3.7	4.5 ± 2.2	5.8 ± 2.3	9.3 ± 3.7	3.7 ± 2.0
p-value	$p = 0.004$	$p = 0.003$	$p < 0.001$	$p = 0.02$	$p < 0.001$	$p < 0.001$	$p = 0.003$	$p < 0.001$	$p < 0.001$	$p = 0.008$
> 6 min										
T_c peak (°C)										
Mean diff	0.76 (0.45 to 1.07) ***	0.77 (0.46 to 1.09) ***	1.36 (0.79 to 1.93) ***	0.85 (0.45 to 1.25) ***	0.91 (0.60 to 1.21) ***	1.31 (0.98 to 1.63) ***	0.70 (0.33 to 1.02) ***	0.89 (0.58 to 1.20) ***	1.38 (1.00 to 1.75) ***	0.53 (0.19 to 0.87) ***
ES	5.8 ± 2.3	5.7 ± 2.3	11.0 ± 3.3	6.6 ± 2.3	6.8 ± 2.7	9.8 ± 2.9	5.8 ± 2.2	6.6 ± 2.7	9.4 ± 3.5	3.5 ± 1.7
p-value	$p < 0.001$	$p < 0.001$	$p = 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.004$
T_c avg (°C)										
Mean diff	0.57 (0.37 to 0.78) ***	0.59 (0.22 to 0.96) ***	1.13 (0.64 to 1.63) ***	0.46 (0.25 to 0.68) ***	0.75 (0.46 to 1.04) ***	1.20 (0.90 to 1.50) ***	0.61 (0.35 to 0.88) ***	0.72 (0.50 to 0.93) ***	1.25 (0.82 to 1.67) ***	0.57 (0.40 to 0.74) ***
ES	4.7 ± 1.9	5.0 ± 2.6	10.0 ± 3.0	4.2 ± 1.5	6.7 ± 2.6	9.8 ± 3.2	6.1 ± 2.3	6.1 ± 2.4	9.2 ± 3.4	4.2 ± 1.7
p-value	$p < 0.001$	$p = 0.005$	$p < 0.001$	$p <0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

BL = baseline; WU = warm-up; CWI = cold water immersion; T_c = core temperature; diff = difference; avg = average; ES = effect size. The likelihood of the observed effect exceeding the smallest worthwhile change (0.2 x between subject SD) when compared to baseline are denoted as; ** = very likely, and *** = most likely.

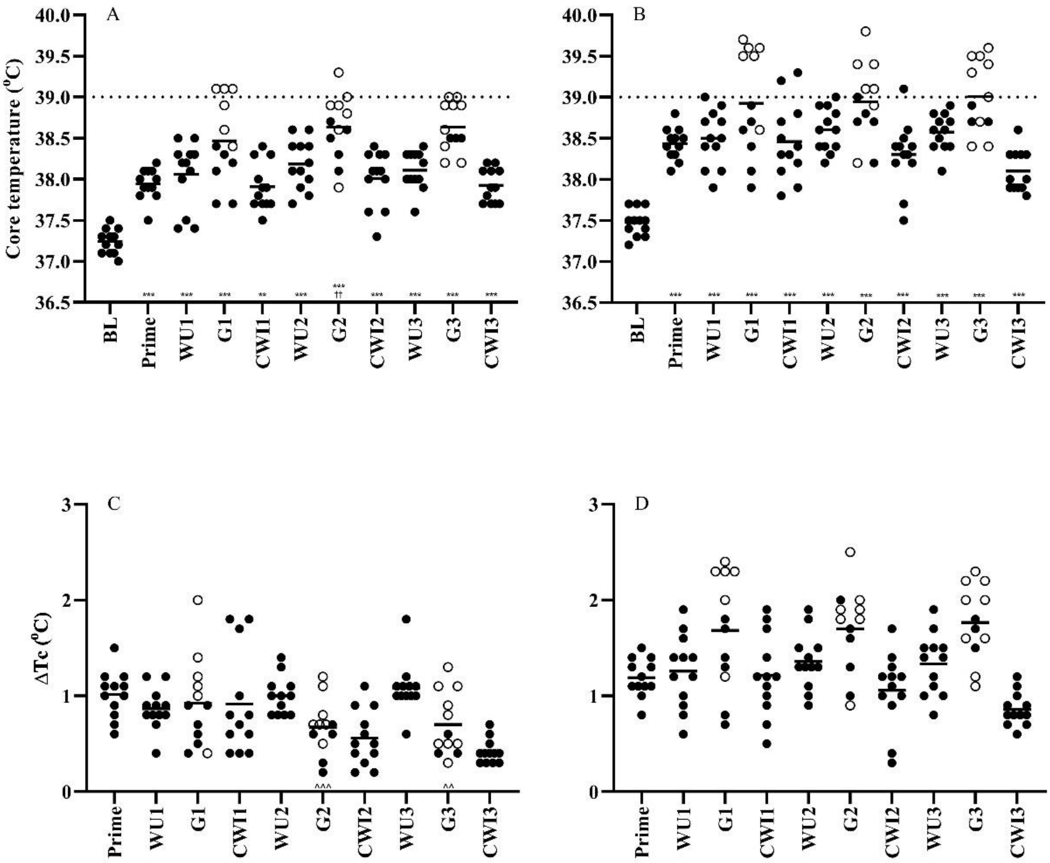


Figure 4.2 Individual average (A), peak (B), Δ period (C) and Δ baseline (D) core temperature (Tc) responses across all periods of the tournament for all players. The solid black line represents the mean for all players. The dashed line represents 39°C. Open circles represent players who had ≥ 6 min match-play. The likelihood of the observed effect exceeding the smallest worthwhile change (0.2 x between subject SD) when compared to baseline are denoted as; ** = *very likely*, *** = *most likely*. When compared to game 1 differences are expressed as; †† = *very likely*. When compared to game 1 only for players with ≥ 6 min match-play, differences are expressed as ^^ = *very likely*, and ^^^ = *most likely*. BL = baseline; WU = warm-up; G = game; CWI = cold water immersion.

Core temperature between WU and games (all players): Differences ($p = 0.04$) in average T_c were seen between games. Players *very likely* (-0.33 ± 0.18) had a lower average T_c in game 1 compared to game 2 [-0.27 (-0.09 – -0.49°C); p = 0.007] with no further T_c derived differences evident between games ($p \geq 0.24$) or between WU ($p \geq 0.13$) across the day, see Figure 4.2.

Core temperature between WU and games (only players > 6 min): Differences ($p = 0.04$) in ΔT_c within period between games were evident. Players *most likely* (0.91 ± 0.31) had a greater ΔT_c in game 1 compared to game 2 [0.39 (0.14 to 0.63ºC); $p = 0.006$] and *very likely* (0.45 ± 0.35) greater ΔT_c in game 1 compared to game 3 [0.30 (0 to 0.61ºC); $p = 0.05$]. No differences for any other T_c-derived measure were evident between games ($p \geq 0.27$) or between WU ($p \geq 0.53$).

Effects of minutes played and external load (GPS) variables on peak T_c (all players): Minutes played were associated with peak T_c ($p = 0.04$). Minutes played *very likely* (0.71 ± 0.28) resulted in an increased peak T_c. There was no association between any of the external load (GPS) variables and peak T_c ($p \geq 0.22$).

Effects of minutes played and external load (GPS) variables on peak T_c (only players ≥ 6 min): No association ($p = 0.11$) between minutes played and peak T_c. There was no association between any of the external load (GPS) variables and peak T_c ($p \geq 0.34$).

External load (GPS) data (only players ≥ 6 min): Differences in average speed ($m \cdot min^{-1}$) ($f = 6.81$, $p = 0.009$), $HSR \cdot min^{-1}$ ($f = 10.74$, $p = 0.002$), $VHSR \cdot min^{-1}$ ($f = 65.86$, $p < 0.001$), and Ave Acc/Dec ($m \cdot s^{-2}$) ($f = 6.17$, $p = 0.007$) were evident (see Table 4.5 for specifics).

Table 4.5 Differences in the external load variables for each game for players who had ≥ 6 min match-play only[game 1 (n = 6), game 2 (n = 7), game 3 (n = 9)]. Data are presented as mean (95% CI). Only significant data is shown.

Period	Game 2	Game 3
Game 1		
HSR·min^{-1}		
Mean diff	5.13 (1.5 – 8.75) **	
ES	2.2 ± 0.87	
P value	$p = 0.01$	
VHSR·min^{-1}		
Mean diff	5.07 (2.48 – 7.66)***	
ES	1.9 ± 0.43	
P value	$p = 0.002$	
Ave Acc/Dec (m·s^{-2})		
Mean diff	0.04 (0.01 – 0.07) ***	
ES	1.8 ± 0.64	
P value	$p = 0.007$	
Game 2		
HSR·min^{-1}		
Mean diff		-7.44 (-3.81 – -11.07) †††
ES		-2.8 ± 0.70
p-value		$p = 0.001$
VHSR·min^{-1}		
Mean diff		-5.17 (-2.43 – -7.91) †††
ES		-1.9 ± 0.55
p-value		$p = 0.002$
m·min^{-1}		
Mean diff		-10.24 (-5.0 – -15.47) †††
ES		-3.9 ± 1.1
p-value		$p = 0.002$

HSR = high speed running; VHSR = very high-speed running, Ave Acc/Dec = average acceleration/deceleration; diff = difference; ES = effect size. The likelihood of the observed effect exceeding the smallest worthwhile change (0.2 x between subject SD) when compared to game 1 are denoted as; ** = very likely, and *** = most likely. When compared to game 2 differences are expressed as; ††† = most likely.

Cooling intervention use (only players ≥ 6 min): For the first CWI players had different exposure times [6 (4 – 6 min)]. The second and third exposure was standardised to 5 and 6 min respectively. Differences were not seen for ΔΔCWI (p = 0.10), see Figure 4.3. Player cooling rates were calculated by dividing the ΔΔCWI by CWI duration (ΔΔCWI $^{\circ}C \cdot min^{-1}$), and then by lean body mass (LBM; ΔΔCWI $°C \cdot min^{-1} \cdot LBM$), see Figure 4.3.

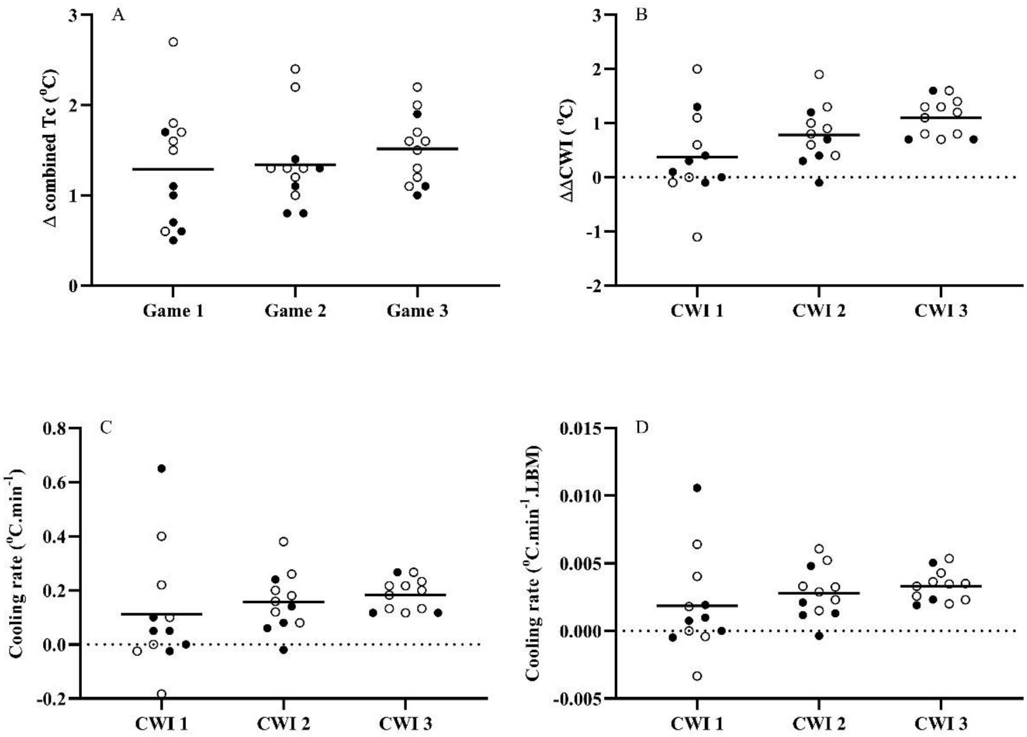


Figure 4.3 Individual Δ combined (A), ΔΔ CWI (B), cooling rate ($^{\circ}C.min^{-1}$) (C) and relative cooling rate ($^{\circ}C.min^{-1} \cdot LBM$) (D) core temperature (Tc) responses to cold water immersion (CWI) and games respectively, for all players. The solid black line represents the mean. Open circles represent players who had ≥ 6 min match-play.

Perceptual data (only players ≥ 6 min): Differences (p = 0.001) in TC between games were evident (see Table 4.3). Players *most likely* (-3.2 ± 0.57) felt more 'comfortable' with the temperature of their body in game 3 compared to game 1 [-1.06 (-0.6 – -1.6); p = 0.001], and game 2 [-1.04 (-0.5 – -1.5); -4.0 ± 1.20; p = 0.001]. No differences were evident regarding RPE (p = 0.30) or TS (p = 0.12), see Figure 4.4.

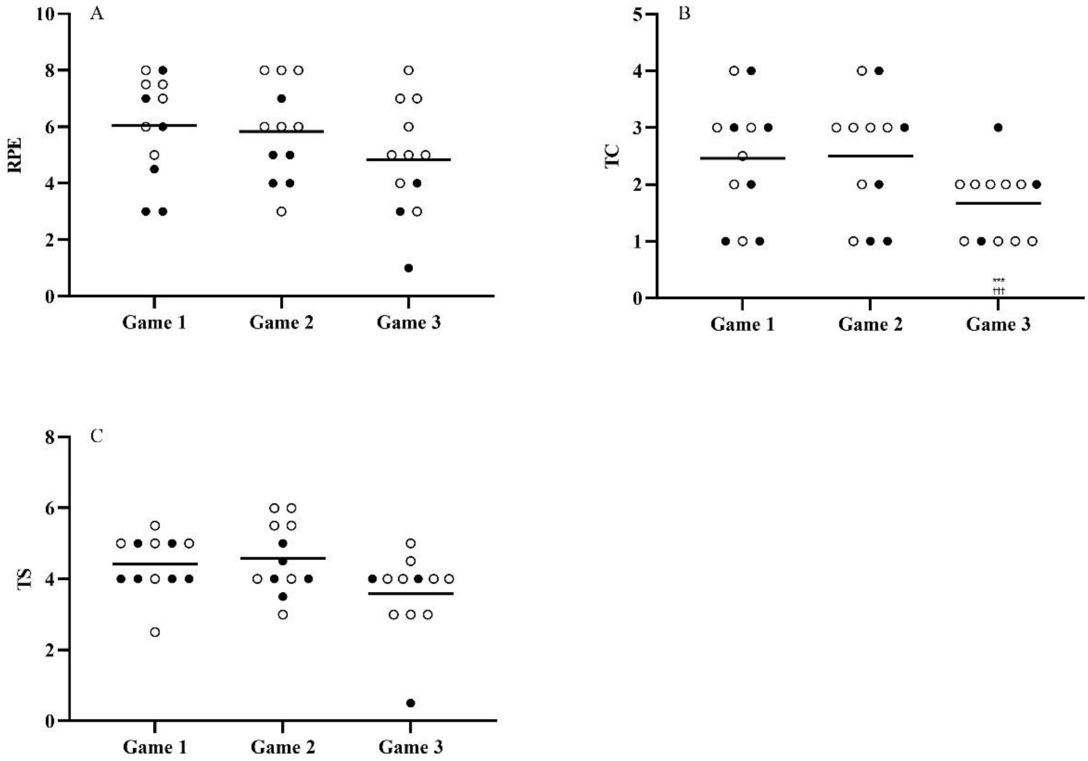


Figure 4.4 Individual RPE (A), TC (B) and TS (C) responses to games 1, 2 and 3 for all players. The solid black line represents the mean. Open circles represent players who had ≥ 6 min match-play. The likelihood of the observed effect exceeding the smallest worthwhile change (0.2 x between subject SD) when compared to game 1 are denoted as; *** = *most likely*. When compared to game 2 differences are expressed as; ††† = *most likely*. RPE = rating of perceived exertion; TC = thermal comfort; TS = thermal sensation.

EHI signs and symptoms: no signs and symptoms of EHI were reported by any player.

DISCUSSION

Approximately 50% of players demonstrated a peak $T_c \geq 39$°C in response to WRWSS match-play within mild WBGT, a magnitude proposed to decrease high-intensity intermittent physical performance (Girard, Brocherie & Bishop 2015); accepting experimental hypothesis (i) and in line with male player data (Taylor, Thornton, et al. 2019). Additionally, the employed CWI protocol left players (≥ 6 min match-play) with a ~1 – 2°C raised T_c, compared to T_c at WU onset (Figure 4.3) in acceptance of hypothesis (ii). Together this demonstrates that despite brief match-play duration within modest WBGT environments, athletes can experience a T_c rise that decreases performance (Girard, Brocherie & Bishop 2015); whilst the CWI protocol employed fails to acquiesce the majority of the acquired T_c rise (e.g., transient hyperthermia) during each game.

Despite modest/low WBGT (18.5 – 20.1°C), high peak T_c values (37.9 – 39.8°C; ~50% ≥ 39ºC) were observed (particularly in those with ≥ 6 min match-play) reaching magnitudes known to reduce repeat sprint ability (Girard, Brocherie & Bishop 2015). Research from other sports sharing high-intensity, intermittent physical demands (soccer and tennis) has reported elite females recording similar peak T_c values (38 – 40°C) (Somboonwong, Chutimakul & Sanguanrungsirikul 2015; Tippet et al. 2011). Given the relationship [*very likely* (0.71 ± 0.28)] seen between minutes played and peak T_c, practitioners and coaches seeking to control player T_c and maximise performance may benefit from pre or per-cooling interventions in the short term or increasing heat tolerance in the longer term. Long-term heat acclimation strategies, although not always practically compatible with training/competition (Casadio et al. 2017), have been shown to provide the greatest protection against performance decrements and EHI (Racinais, Alonso, et al. 2015).

Alternatively, opting for an alternate WU environment with more controlled conditions (e.g., indoor) or modifying the WU volume/duration/intensity and thus reducing body metabolic heat storage from it, may provide a greater T_c reserve until a ≥ 39°C is reached during match-play (i.e., players start the match-cooler). Indeed, body heat storage from the employed WU could be considered 'too much' (Figure 4.2) given a peak T_c of 39°C was seen for two players and exceeding 38.5°C in > 50% of players. Practically, however, such titration of WU may be challenging to achieve, given often divergent player needs and the dynamic nature of individual T_c change across the day. There are obvious practical and logistical advantages in allowing all squad members to complete the same WU, as a team, during a WRWSS match day. This may be possible if augmented heat loss was facilitated during the WU, which through the use of a phase change cooling vest has shown promise as an effective and ecologically valid strategy to reduce T_c, without altering selected WU characteristics or performance measures in elite men's rugby sevens (Taylor, Stevens, et al. 2019). However, specific to the WRWSS there is currently no evidence regarding the efficacy of such interventions, which may be different to those presented for elite male sevens players (Taylor, Stevens, et al. 2019) (for reasons outlined in the introduction). Further, the T_c responses discussed above from modest WBGT environments would likely be exacerbated in high WBGT environments, such as those experienced commonly in other WRWSS tournaments and expected at Tokyo 2020 (Kakamu et al. 2017; Kashimura, Minami & Hoshi 2016). During or proximal to the warm-up, strategies to minimise hyperthermia risk and/or increase the T_c heat-sink (and associated favourable perceptual changes) prior to competition, appear prudent. These include, amongst others, wearing a phase change cooling vest, ice-slurry ingestion after the sweat response has been observed, ice towel application, performing the warm-up in an air-conditioned indoor environment (with simulated wind velocity), or outdoors with appropriate wind velocity (N.B. such approaches require extensive piloting and should not compromise the desired outcome of an effective warm-up).

Quickly removing the majority of the rise in T_c due to match-play appears prudent, given the accumulation of T_c between games, despite similar work rates across games. Indeed, average T_c values in the present data were *most likely* higher in game 2 than game 1, and *very likely* higher in game 3 than game 2 (players with ≥ 6 minutes involvement time), in support of similar findings in elite men's rugby sevens who did not perform any in-competition cooling (Taylor, Thornton, et al. 2019). However, the employed CWI protocol left players (≥ 6 min match-play) with a ~1 – 2°C raised T_c compared to T_c at WU onset (Figure 4.3). Evidently, the lack of individualisation of CWI time (e.g., by match-play minutes) and players only immersing themselves to hip height, contributed to the cooling responses seen (despite the CWI water temperature range of 6.1 – 7.3°C). Piloting both these CWI protocol modifications [e.g., individualised immersion based on minutes played and shoulder-depth immersion (to maximise conductive heat dissipation (Zhang et al. 2015))] is recommended, to produce practice-ready, individualised solutions.

Although previous research has indicated that high T_c values (>39°C) are detrimental to repeat and intermittent sprint performance (Girard, Brocherie & Bishop 2015), the present study found no link between changes in T_c and reductions in external load measures (GPS). This could be due to individual variation in the relationship between high T_c and repeat and intermittent sprint performance as discussed elsewhere (Girard, Brocherie & Bishop 2015). Similarly, the technical/tactical contextual factors of the matches influencing the physical demands (Henderson et al. 2018), the influence of menstrual cycle phase that wasn't accounted for (Charkoudian et al. 2017; Janse et al. 2012), or a sample size ($n = 12$; 3 matches) too small to detect a meaningful change in external load (GPS) metrics (Biau, Kernéis & Porcher 2008) may also explain this finding. A lack of robust data regarding the relationship between altered thermal perceptions and their effect on performance capacities in elite athletes (e.g., particularly repeat sprint ability), renders performance-based inferences on perceptual measures uncertain within the present design; although reductions in thermal sensation without accompanying physical body temperature decreases can within some scenarios (predominately endurance exercise) prove ergogenic to exercise performance in the heat (Stevens et al. 2018; Taylor, Stevens, et al. 2019). Future research should look to include multiple match-days and/or tournaments so contextual variance due to technical/tactical factors is less pronounced, and greater statistical power can be attained.

PRACTICAL APPLICATIONS

- Modifying the WU volume/duration/intensity to reduce body heat storage may provide a greater T_c reserve until a ≥ 39ºC is reached during match-play (i.e., players start the match-cooler).
- Individualised CWI protocols based on minutes played and shoulder-depth immersion is recommended to produce a practice-ready individualised solution to heat dissipation.

CONCLUSIONS

Like their male counterparts, elite female rugby sevens athletes experience high T_c during WU and matches on WRWSS match days, even in modest WBGT environments. Strategies and modifications to match-day protocols likely to result in improved thermoregulatory function, and subsequent physical performance for athletes are available, yet they lack empirical data to inform practice with specificity to the WRWSS.

CHAPTER 5 | ADDITIONAL CLOTHING INCREASES HEAT-LOAD IN ELITE FEMALE RUGBY SEVENS PLAYERS

Henderson, M.J., Chrismas, B.C.R., Stevens, C.J., Novak, A.R., Fransen, J., Coutts, A.J. & Taylor, L. (2020). Additional clothing increases heat-load in elite female rugby sevens players. International Journal of Sports Physiology & Performance, 16(10): 1424 – 1431.

ABSTRACT

Purpose: To (1) determine whether elite female rugby sevens players are exposed to T_c during training in the heat that replicates the temperate match demands previously reported, and (2) investigate whether additional clothing worn during a hot training session meaningfully increases the heat load experienced. **Methods:** A randomised parallel group study design was employed with all players completing the same approximately 70-minute training session (27.5 – 34.8°C wet bulb globe temperature) and wearing a standardised training ensemble (synthetic rugby shorts and training tee [control (CON); n = 8)] or additional clothing (standardised training ensemble plus compression garments and full tracksuit [additional clothing (AC); n = 6]). Groupwise differences in T_c, sweat rate, GPS-measured external locomotive output, rating of perceived exertion (RPE), and perceptual thermal load were compared. **Results:** Mean ($p = 0.006$, $\eta_p^2 = 0.88$) and peak ($p < 0.001$, $\eta_p^2 = 0.97$) T_c was higher in AC compared to CON during the training session. There were no differences in external load [F (4, 9) = 0.155, $p = 0.956$, Wilk's Λ = 0.935, $\eta_p^2 = 0.06$] or sweat rate ($p = 0.054$, Cohen's $d = 1.09$). Higher RPE ($p = 0.016$, Cohen's $d = 1.49$) was observed in AC compared to CON. No EHI symptomology was reported in either group. **Conclusions:** Player T_c is similar between training performed in hot environments and match play in temperate conditions when involved for > 6 min. Additional clothing is a viable and effective method to increase heat strain in female rugby sevens players without compromising training specificity or external locomotive capacity.

INTRODUCTION

Physical preparation best practices for hot and humid competition conditions require carefully prescribed and controlled heat stress [i.e., heat acclimation or acclimatisation; (HA)] to promote optimal performance (Racinais, Alonso, et al. 2015; Tyler et al. 2016). Appropriate training prescription [typically active (i.e., exercise) heat load (Gibson et al. 2019)] promotes physiological adaptations likely to benefit physical capacity/performance in such environments [e.g., reduced resting/exercising T_c and heart rates (HR), earlier and greater sweat response, greater plasma volume and exercise capacity (Tyler et al. 2016)]. Typical physiological responses to match play in elite women's rugby sevens include high T_c (peak T_c responses from match play: 37.9 – 39.8°C) (Henderson et al. 2020), and HR intensities (most playing time spent between 81 and 90% of maximal HR) (Suarez-Arrones et al. 2012). Whether routine training for rugby sevens in hot conditions generates the high thermal load observed in elite female match-play [peak T_c median (range) when involved in > 6 min match play: 39.3°C (38.2 – 39.8°C)] within modest wet bulb globe temperatures [WBGT; 18.5 – 20.1°C (Henderson et al. 2020)], has not been established. Evidently, any disparity in this relationship has ramifications for physical preparation strategies - especially - relative to the likely higher T_c that would be observed in this population during match-play in higher WBGT environments (e.g., Tokyo Olympics) compared to the predominately temperate match-play data currently available (Henderson et al. 2020; Taylor, Thornton, et al. 2019).

Common barriers to best practice HA preparation in team sports include financial (travelling to appropriate locations or hiring facilities with simulated environmental rooms can be expensive) and time constraints (team sports often have congested preparation/competition schedules and are commonly time-poor). A practical option available to all practitioners and teams is wearing additional clothing during physical preparation. This intervention promotes psycho-physiological responses implicated in successful HA protocols [e.g., elevated: T_c and skin temperature (T_{sk}), sweat rate, thermal sensation/discomfort, and HR (Tyler et al. 2016)] without the need for hot ambient conditions (Tyler 2019). Therefore, additional clothing may provide a practically compatible and cheap tool to offset (partially or otherwise) any potential thermal mismatch between training and matches, increasing training specificity. Many athletes and teams preparing for the Olympic Games in Tokyo [expected to be the hottest modern Olympics to date; ~30°C and relative humidity exceeding 75% (Taylor, Carter & Stellingwerff 2020)] will be training in temperate or cold environments not conducive to HA. Data regarding the thermal dose response to training in additional clothing compared to a control condition is generally lacking within elite team sport populations, particularly females, thus evidence-based decision-making and practice within this paradigm is challenging.

This study aims to (1) determine whether elite female rugby sevens players are exposed to a T_c during training in the heat that replicates the temperate match demands previously reported (Henderson et al. 2020); and (2) investigate whether additional clothing worn during a full rugby sevens training session in the heat increases the heat load experienced. It is hypothesised that (i) peak T_c and change from baseline to peak during training will not reach the magnitudes observed from available match play data, and (ii) additional clothing worn during an on-field rugby sevens training session will significantly increase heat load compared to control without any effect on GPS-derived external locomotive output.

METHODS

SUBJECTS

Data were collected from a total of 14 seasonally heat-acclimatised female athletes (see Table 5.1 for details) from a single 2018-19 World Rugby Women's Sevens Series team based in Sydney, Australia. The full population of professionally contracted international female rugby sevens athletes in the country, fit at the time of data collection, were recruited. Written informed consent was provided for the project under ethical approval from the Southern Cross University (ECN-18-216) and the University of Technology Sydney (ETH19-4051) Human Research Ethics Committees in the spirit of the Helsinki Declaration.

Table 5.1 Player characteristics, anthropometry, and body composition. Data are presented as median (minimum – maximum).

Measure	Control	Additional Clothing
Age (y)	24 (19 – 29)	23 (17 – 30)
Height (m)	1.69 (1.65 – 1.74)	1.69 (1.65 – 1.71)
Body mass (kg)	67.8 (59.2 – 74.0)	67.5 (63.9 – 77.7)
Sum SF (mm)	70.1 (38.9 – 82.5)	69.6 (51.6 – 84.3)
Triceps SF (mm)	6.8 (3.8 – 11.8)	7.4 (4.8 – 10.1)
Subscapular SF (mm)	9.4 (6.5 – 15.2)	9.6 (6.9 – 13.5)
Bicep SF (mm)	4.2 (2.9 – 6.7)	4.3 (3.2 – 6.0)
Supraspinale SF (mm)	8.2 (5.2 – 16.8)	8.5 (3.8 – 11.3)
Abdomen SF (mm)	11.7 (8.7 – 20.0)	11.9 (7.6 – 13.6)
Thigh SF (mm)	17.2 (8.5 – 26.0)	17.1 (14.8 – 25.4)
Calf SF (mm)	9.1 (3.0 – 12.0)	8.1 (6.0 – 12.0)
Body fat (%)	19.1 (14.7 – 25.4)	20.4 (13.6 – 22.0)
LBM (kg)	54.9 (49.8 – 63.1)	54.4 (49.9 – 62.5)

SF = skinfold; LBM = lean body mass

DESIGN

A randomised parallel-group study design was employed with all players simultaneously completing the same 70 min training session, wearing (i) a standardised training ensemble (synthetic rugby shorts and training tee; CON) or (ii) additional clothing [(i) plus compression garments and full tracksuit; AC]. Players had been in the same time zone ≥ 14 days prior to the training session, thus circadian misalignment in T_c was not a confounding influence. In line with common elite team sport practice, menstrual cycle could not be standardised.

METHODOLOGY

Players ingested an e-Celsius™ telemetric capsule (BodyCap, Caen, France) the night prior to the training session. T_c data was only included within the statistical model when ≥ 5 hours had elapsed post-ingestion, a criterion used previously to ensure the capsule was in the lower intestine (Byrne & Lim 2007; Henderson et al. 2020; Taylor, Thornton, et al. 2019). T_c was sampled at 30 s intervals, with data downloaded at the end of the training session via a wireless data receiver (e-Viewer, BodyCap, Caen, France). Capsules were prepared, calibrated, and handled as outlined previously (Henderson et al. 2020; Taylor, Thornton, et al. 2019; Travers et al. 2016). The e-Celsius^{TM} system has been determined valid and reliable for intermittent-running exercise (Travers et al. 2016), as well as excellent validity (ICC 1.00), test-retest reliability (ICC 1.00) and inertia in water bath experiments between 36°C and 44°C (Bongers et al. 2018), and has been used previously within elite rugby sevens matches (Henderson et al. 2020; Taylor, Thornton, et al. 2019) and training (Taylor, Stevens, et al. 2019). In the case of the capsule having been passed prior to the training session (this occurred for one athlete from AC and two from CON), T_c data was not able to be collected.

Wet bulb globe temperature (WBGT) (SD-2010, Reed Instruments, Wilmington, NC, USA) was obtained immediately prior to, during and post-training session. Conditions across the data collection period were generally hot (27.8 – 34.8°C WGBT). Signs and symptoms of exertional heat illnesses (EHI) were collected following the training session using a modified survey instrument (Périard et al. 2017). Specifically, the athletes were asked in a yes/no manner if they had experienced (i) cramping; (ii) vomiting; (iii) nausea; (iv) severe headache; (v) collapsing/fainting; or (vi) any other symptom that might relate to heat illness (Périard et al. 2017).

Whole-body sweat loss was quantified by determining the change in body mass pre- and post-training (assuming a fluid volume of 1L = 1 kg). Players were asked to urinate and/or defecate, if necessary, prior to pre-training measurement and not again until post-training measurement. Body mass was measured wearing only underwear, immediately before and after the training session using calibrated scales (BWB-800-S, Tanita, Tokyo, Japan). Each player was provided with an individually named drink bottle that was weighed before and after training to establish the volume consumed during the training session. Body mass loss was corrected for both fluid intake and urine output but was not corrected for respiratory and metabolic water loss/gain. Drinking behaviour was monitored by the researchers and practitioners to ensure players only drank from their own bottles and did not spit water out or pour water on themselves. Sweat rate was calculated by dividing the corrected body mass loss from the session by the duration in hours.

Activity profiles during the session were measured using 10 Hz GPS devices (EVO, GPSports, Canberra, Australia). These have shown good inter-unit reliability for distance (in metres; coefficient of variation [CV] ± 90% confidence limits: 0.2 ± 1.5%), average speed (in metres per minute [$m \cdot min^{-1}$]; 0.2 ± 1.5%), max velocity (in metres per second [$m \cdot s^{-1}$]; 0.2 ± 1.5%), high-speed running (distance covered > 5 $m \cdot s^{-1}$; 0.5 ± 1.5%), and average acceleration/deceleration (in metres per second squared [$m \cdot s^{-2}$]; 1.2 ± 1.5%) (Thornton et al. 2019). Each unit was assigned to an individual player and worn underneath their training shirt in a small upper-body garment custom designed by the device manufacturer, positioning the unit between the scapula blades of the player. Following the session, stored data were downloaded from the devices using the manufacturer's proprietary software (GPSports Console, GPSports, Canberra, Australia). Metrics exported from the GPS data included training duration (min), average speed ($m \cdot min^{-1}$), high-speed running per minute ($HSR \cdot min^{-1}$; average distance covered > 5 $m \cdot s^{-1}$ per minute), very high-speed running per minute ($VHSR \cdot min^{-1}$; average distance covered > 6 $m \cdot s^{-1}$ per minute), and average absolute acceleration/deceleration (Ave Acc/Dec; $m \cdot s^{-2}$).

Thermal sensation (TS) was measured using a 17-point category ratio scale (where 0 = 'unbearably cold' and 8 = 'unbearably hot') (Young et al. 1987). Thermal comfort (TC) was measured using a 10-point ordinal scale (where 1 = 'comfortable' and 10 = +1 above 'extremely uncomfortable') (Borg 1982). Both TS and TC represent how players were feeling when asked (i.e., not a session average). Session rating of perceived exertion (RPE) was measured using the Category-Ratio scale (CR-10; where 0 = rest and 10 = maximal) (Borg 1982).

STATISTICAL ANALYSES

All statistical analyses were performed, and figures were created, using R statistical software (R Core Team 2022). Descriptive statistics are reported as median and range (min – max) unless otherwise stated. Individual player T_c was collected and averaged for each period, with peak T_c values extracted and individual player change from baseline calculated. Differences between present findings and available match data previously reported (Henderson et al. 2020) were assessed using a one-tailed Welch's *t*-test to account for the observed unequal variances.

Core temperature: A linear mixed effects analysis was performed using the {lme4} (Bates et al. 2015) and {lmerTest} (Kuznetsova, Brockhoff & Christensen 2016) packages in R statistical software (R Core Team 2022) to determine the relationship between wearing additional clothing during training and T_c measures at different time points during the session (baseline, training average, and training peak). As fixed effects, experimental group and timepoint (with interaction term) were entered into the model including a random intercept to specify repeated measures for each player. P-values were obtained by Kenward-Roger approximation (Kenward & Roger 1997) which has been shown to produce acceptable Type 1 error rates even for smaller samples (Luke 2017). Approximate partial eta squared effect sizes (η_p^2) were converted from test statistics and degrees of freedom using the {effectsize} R package (Ben-Shachar, Makowski & Lüdecke 2020).

Sweat rate: A one-tailed Mann Whitney U test was used to determine if AC increased sweat rate compared to CON. Normality and equal variance assumptions were checked using the Shapiro-Wilk Test of Normality and Levene's Test respectively, and the non-parametric Mann-Whitney U test was chosen to account for the observed violation of normality.

External load: A multivariate analysis of variance was performed on the collected GPS metrics ($m \cdot min^{-1}$, $HSR \cdot min^{-1}$, $VHSR \cdot min^{-1}$, and Ave Acc/Dec) to assess group differences in locomotion. Assumptions of homogeneity and multivariate normality were checked using Box's Homogeneity of Covariance Matrices Test ($p = 0.666$) and Shapiro-Wilk Multivariate Normality Test ($p = 0.061$), respectively.

Perceptual measures: A one-tailed Mann-Whitney U test was performed to assess differences in RPE between AC and CON. As TS and TC are ordinal data, it would be inappropriate to make statistical inferences from tests requiring a continuous dependent variable [despite similar data sets using an array of these approaches previously (Périard et al. 2014b; Stephens, Argus & Driller 2014)]. To perform the appropriate ordinal regression on this data, a larger sample would be required and is likely not possible with one rugby sevens team and 17-point (TS) and 10-point (TC) scales. Therefore, TS and TC are provided as a central tendency (median) and dispersion (range) (see Figure 5.5) and are discussed only in raw unit changes/comparisons.

RESULTS

Raw data for T_c, sweat rate, external load, and perceptual measures for all players are presented in Tables 5.2, 5.3, and 5.4, respectively.

Table 5.2 Core body temperature and sweat rate across each time point and group.Data are presented as median (range) for all players.

Timepoint	Group	T_c (°C)	ΔT_c from Baseline (°C)	Sweat rate ($L \cdot hr^{-1}$)
Baseline	Control	37.2 (36.7 – 37.5)	N/A	N/A
	Additional Clothing	37.1 (36.6 – 37.2)	N/A	N/A
Training Average	Control	38.2 (37.7 – 38.4)	1.0 (0.9 – 1.2)	1.41 (1.06 – 1.73)
	Additional Clothing	38.4 (38.1 – 38.7)	1.4 (1.2 – 1.6)	1.64 (1.46 – 2.66)
Training Peak	Control	39.2 (38.7 – 39.4)	2.0 (1.9 – 2.4)	N/A
	Additional Clothing	39.8 (39.5 – 40.4)	2.6 (2.5 – 3.3)	N/A

T_c: core temperature

Table 5.3 Global Positioning Systems measures between experimental groups during the session. Data are presented as median (range) for all players.

Group	$m \cdot min^{-1}$	$HSR \cdot min^{-1}$	$VHSR \cdot min^{-1}$	Ave Acc/Dec
Control	44.6 (36.7 – 45.9)	1.5 (1.2 – 2.0)	0.40 (0.16 – 0.69)	0.33 (0.29 – 0.35)
Additional Clothing	41.8 (39.3 – 48.5)	1.5 (1.4 – 1.9)	0.48 (0.27 – 0.66)	0.32 (0.28 – 0.38)

$m \cdot min^{-1}$: metres per minute; $HSR \cdot min^{-1}$: metres per minute covered at greater than 5 metres per second; $VHSR \cdot min^{-1}$: metres per minute covered at greater than 6 metres per second; Ave Acc/Dec: average acceleration/deceleration in $m \cdot s \cdot s^{-2}$.

Table 5.4 Perceptual measures recorded pre- and post-session between experimental groups. Data are presented as median (range) for all players.

Period	Group	RPE	Thermal Sensation	Thermal Comfort
Pre	Control	NA	4.0 (3.0 – 5.5)	1.0 (1.0 – 1.0)
	Additional Clothing	NA	4.0 (3.0 – 4.5)	1.0 (1.0 – 1.0)
Post	Control	8 (7 – 9)	7.0 (6.5 – 7.5)	6.5 (5.0 – 7.0)
	Additional Clothing	9 (8 – 10)	7.3 (7.0 – 8.0)	8.5 (8.0 – 9.0)

RPE: Rating of perceived exertion

Core temperature: The association between wearing additional clothing and session time point (with interaction) on player T_c is presented in Figure 5.1 and Table 5.5. This model displayed a marginal R^2 value (indicating explained variance from fixed effects only) of 0.94 and a conditional R^2 value (indicating explained variance from both fixed and random effects) of 0.98. The baseline T_c reading did not differ between groups [CON: 37.2°C (36.7 – 37.5), AC: 37.1 (36.6 – 37.2); p = 0.356], but the mean and peak T_c of AC [mean: 38.4°C (38.1 – 38.7°C); peak: 39.8°C (39.5 – 40.4°C)] was higher compared to CON [mean: 38.2°C (37.7 – 38.4°C); peak: 39.2°C (38.7 – 39.4°C)] during the training session (p = 0.006, η_p^2 = 0.88 and p < 0.001, η_p^2 = 0.97 respectively). Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality, and the Shapiro-Wilk test performed on the model residuals suggested no evidence of non-normality (p = 0.798).

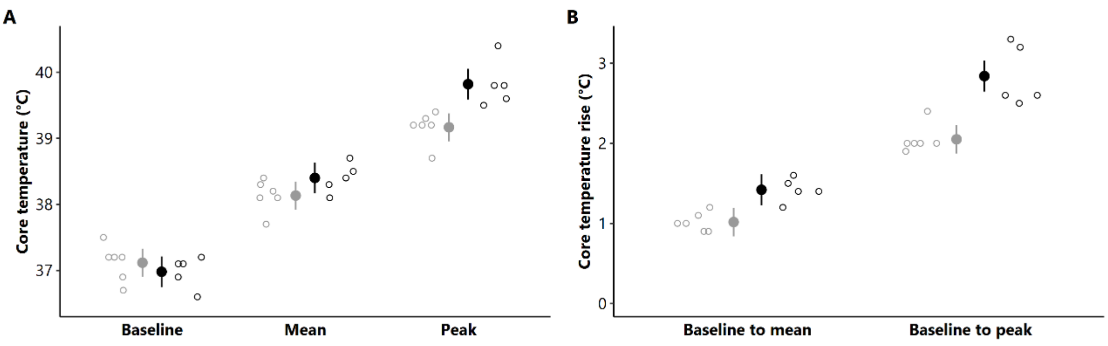


Figure 5.1 Individual baseline, mean, and peak core temperature (5.1A) and change from baseline to mean and peak core temperature (5.1B) for all players. Filled circles represent predicted group means from a linear mixed model at each time point, lines represent a 95% confidence interval of the predicted group means, and unfilled circles represent individual data for additional clothing (black) and control (grey) conditions.

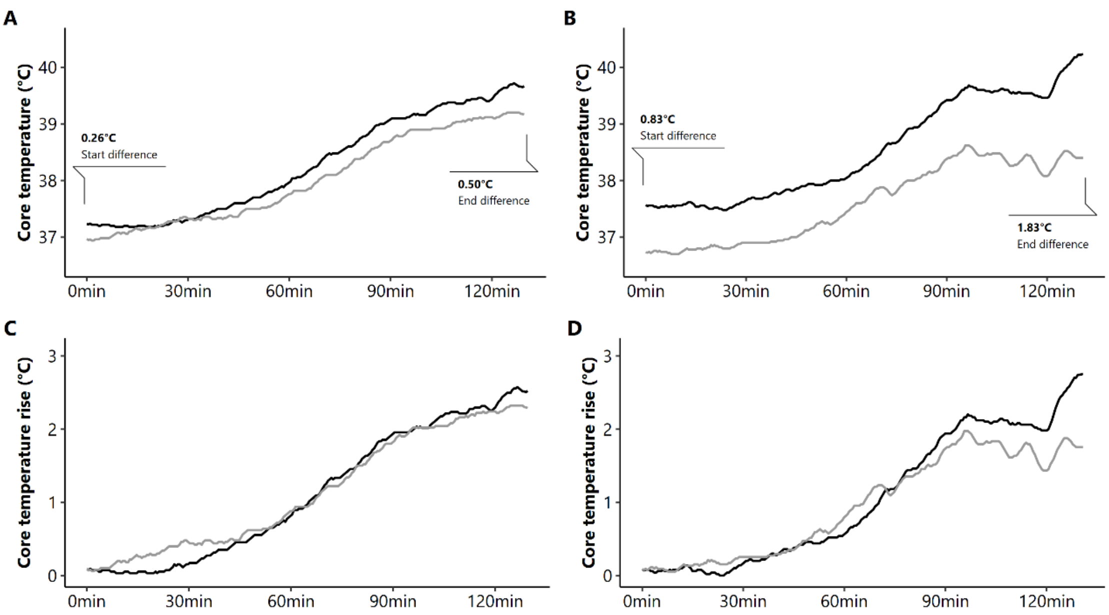


Figure 5.2 Individual core temperature traces during the training session for athletes recording the median peak core temperature (raw: 5.2A; delta: 5.2C) and largest peak core temperature disparity (raw: 5.2B; delta: 5.2D) in the additional clothing group (black) and control group (grey). Extremes of core temperature responses in 5.2B and 5.2D are shown to demonstrate variability between individuals. Five-point moving mean smoothing was applied to the data to minimise noise.

Table 5.5 Linear mixed-effects model assessing the effect of experimental group and timepoint (with interaction) on player core temperature.

Predictors	**Estimates (95% CI)**	**std. Error**	**t**	**df**	**p**	**η_p^2 (95% CI)**	**ES interpretation**
(Intercept)	37.12 (36.90 – 37.33)	0.11	343.54	21.23	**<0.001**		
Control			*Reference*				
Intervention	-0.14 (-0.45 – 0.18)	0.16	-0.85	21.23	0.408	0.05 (0.00 – 0.36)	*small*
Group: Intervention x Timepoint: Training Average	0.40 (0.15 – 0.66)	0.13	3.1	26.89	**0.006**	0.88 (0.75 – 0.93)	*large*
Group: Intervention x Timepoint: Training Peak	0.79 (0.54 – 1.04)	0.13	6.08	26.89	**<0.001**	0.97 (0.93 – 0.98)	*large*
Baseline			*Reference*				
Training Average	1.02 (0.84 – 1.19)	0.09	11.6	26.89	**<0.001**	0.35 (0.04 – 0.61)	*large*
Training Peak	2.05 (1.88 – 2.22)	0.09	23.39	26.89	**<0.001**	0.67 (0.37 – 0.81)	*large*
$N_{Players}$			11				
Observations			33				
Marginal R^2 / Conditional R^2			0.937 / 0.979				

CI: confidence interval; *df*: degrees of freedom; η_p^2: approximate partial eta squared; *ES*: effect size

Sweat rate: No difference in sweat rate was found between groups (median in CON = 1.41 L/hr, the median in AC = 1.64 L/hr; *U* = 11.0; *p* = 0.054, Cohen's *d* = 1.09).

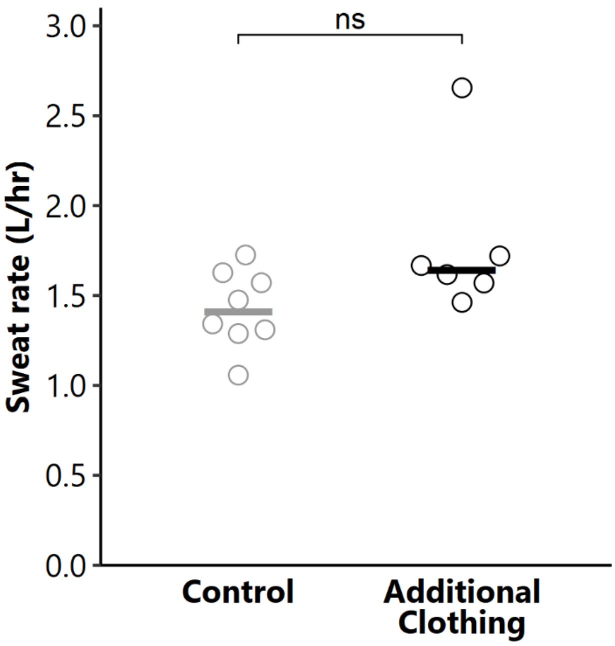


Figure 5.3 Individual sweat rates for all players. Solid horizontal lines represent the group median and circles represent individual data for additional clothing (black) and control (grey) conditions. L/hr = Litres per hour; ns = non-significant.

External load: The multivariate analysis found no difference in external load between AC and CON (F [4, 9] = 0.155, *p* = 0.956, η_p^2 [95% CI] = 0.06 [0.00 – 0.13]; Wilk's Λ = 0.935).

Perceptual measures: There was an increase in RPE values in AC compared to CON (*U* = 8.00, *p* = 0.016, Cohen’s *d* = 1.49).

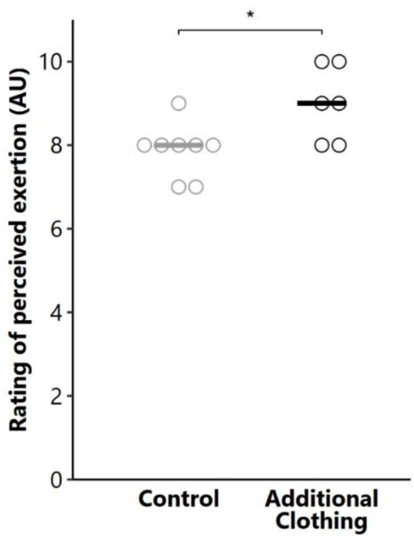


Figure 5.4 Individual post-session rating of perceived exertion for all players. Solid horizontal lines represent the group median and circles represent individual data for additional clothing (black) and control (grey) conditions. AU = arbitrary units; * = $p < 0.05$.

A raw unit increase in TS was 3 (3 – 5) in AC and 3 (2 – 4) in CON. A raw unit increase in TC was 7.5 (7 – 8) in AC and 5.5 (4 – 6) in CON.

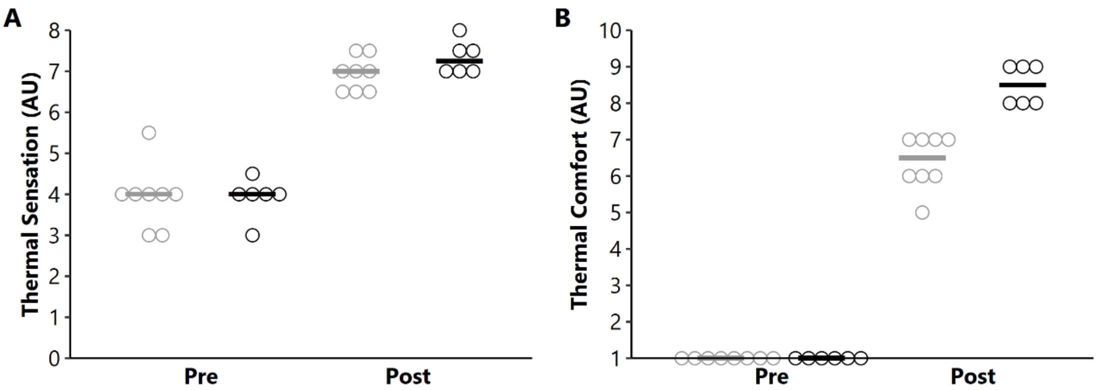


Figure 5.5 Individual pre- and post-session thermal sensation (5.5A) and thermal comfort (5.5B) for all players. Solid horizontal lines represent group median and circles represent individual data for additional clothing (black) and control (grey) conditions. AU = arbitrary units.

No EHI symptomology was reported in either group.

DISCUSSION

The peak T_c [39.2°C (38.7 – 39.4°C)] and change from baseline to peak T_c [2.0°C (1.9 – 2.4°C)] observed throughout the training session (27.5 – 34.8°C WBGT) in CON (i.e., normal training clothes) did not differ to the magnitudes reported from temperate match play (18.5 – 20.1°C WBGT) when involved for at least 6 min [peak: 39.3°C (38.2 – 39.8°C), p = 0.433; change from baseline to peak: 2.0°C (0.9 – 2.5°C), p = 0.906 (Henderson et al. 2020)]. This rejects experimental hypothesis (i) that theorised T_c in hot training would not reach magnitudes observed during temperate match play [although the contrasting ambient WBGT between the present study (27.5 – 34.8 WBGT) and the previously published match-play data (Henderson et al. 2020) (18.5 – 20.1 WBGT) ensures these comparisons must be carefully interpreted]. Thermal load (as measured by player T_c), TS, and TC, were greater in AC compared to CON, without compromising training specificity or external locomotive capacity (i.e., GPS), in support of experimental hypothesis (ii).

As sporting teams approach competition, training specificity is increasingly prioritised to maximise transfer to sporting movements (Brearley & Bishop 2019). As such, practitioners tasked with preparing rugby sevens teams for tournaments should be aware of the likely thermal demands of tournaments (combination of predicted approximate physical demands and environmental conditions) and ensure appropriate training (e.g., HA) occurs to develop the necessary adaptations to maximise performance and protect athlete health [particularly in female athletes who may be more susceptible to hyperthermia (Henderson et al. 2020)]. This is the first study to directly compare player T_c recorded in training to the only available match play T_c data in women's rugby sevens. The findings support that training in hot environments (27.5 – 34.8°C WBGT in the current study) may provide comparable heat stress to the previously reported temperate match-play data, albeit emphasising an important distinction, in temperate (18.5 – 20.1°C WBGT) match-play conditions (Henderson et al. 2020) compared to the hot (27.5 – 34.8°C WBGT) training conditions in the present study (Figure 5.1). Given training in hot conditions generates a comparable thermal load to temperate match-play, it seems logical [as shown elsewhere (Aughey, Goodman & McKenna 2014)] that the responses to matches in hot conditions would likely not be replicated within these training conditions (i.e., players would not get hot enough in training to mimic thermal demands on hot matchdays). This expectation is based on the higher T_c observed during higher ambient temperatures in Australian rules football with comparable intermittent, high-intensity, bioenergetic demands (Aughey, Goodman & McKenna 2014) to rugby sevens (Suarez-Arrones et al. 2012). This may require a further intervention such as wearing additional clothing during hot training to facilitate the desired phenotypic HA signals and adaptations (e.g., decreased T_c and HR at a given intensity etc.), which in turn, protect impaired performance capacity and EHI associated with exercise-induced hyperthermia (Racinais, Alonso, et al. 2015).

Longer term (> 14 days) HA strategies have been shown to provide the greatest protection to performance decrements and EHI (Racinais, Alonso, et al. 2015), yet traditionally have often been impractical in elite team sports due to highly demanding physical preparation programs, pre-set competition schedules, and travel demands (Casadio et al. 2017). The observed increases in T_c and perceived thermal load in AC are likely to stimulate a greater physiological response compared to CON and may contribute to more pronounced HA adaptations or faster procurement of a fully HA phenotype (Tyler et al. 2016); N.B. a higher HA-session T_c does not always promote 'greater' HA adaptations (Gibson et al. 2015). These findings provide proof of concept for additional clothing and its ability to increase the thermal load and elicit associated perceptual changes within the utilised population. Adoption of additional clothing within training scenarios may (subject to further confirmatory work) solve some, but not all, common challenges to practice regarding barriers to HA protocols within team sports. Future work should use a repeated measures design to provide more detail on the physiological (including key variables associated with HA not adopted within the present design, e.g., HR, skin temperature, etc.), technical, and training load responses to an acute session. This could precede more prolonged additional clothing implementations within a team sport scenario and determine whether such an intervention can elicit a fully HA phenotype.

The AC group in the present study reached very high peak T_c values (range: 39.5 – 40.4°C) but external locomotive work output was not affected compared to CON (with five of the ten drills completed after warm-up involving a degree of internally governed locomotion). It has been proposed that a T_c >39°C can compromise central nervous system function (Girard, Brocherie & Bishop 2015), repeat sprint ability [<60 s between efforts (Drust et al. 2005; Girard, Brocherie & Bishop 2015)], and intermittent sprint performance [60 – 300 s between efforts (Sunderland & Nevill 2005)] but the present study was not able to reproduce these locomotive movement decrements, nor any undesirable EHI associated pathologies, despite surpassing the T_c threshold proposed to affect performance (Girard, Brocherie & Bishop 2015). A possible explanation for this finding is that some CON group T_c values also surpassed 39°C (range: 38.7 – 39.4), although not to the same magnitude as AC, suggesting a potential non-linear relationship between T_c (>39°C) and locomotive capacity. Similarly, meaningful differences in external locomotive capacity may be hidden by the large variability observed in physical performance for rugby sevens due to contextual sport demands (Henderson et al. 2019). This makes meaningful inferences from interventions difficult to ascertain as key physical performance measures during invasive team sports (e.g., high-speed running) show poor reliability and demand practically unrealistic sample sizes [e.g., elite soccer sample required is 80 players (Gregson et al. 2010)].

Whilst this study provides proof of concept that wearing additional clothing can increase the thermal load and its perception, the lack of a repeated measures design and a small sample of athletes (n = 14) from one team with likely similar acclimatisation status limit the broader generalisability of the findings. Although the sample size in the present investigation is limited, it represents the full population of professionally contracted international female rugby sevens athletes in the country, that were fit, at the time of data collection. Future research using a larger sample of athletes from different teams and home climates (multi-team studies likely required, albeit challenging to deliver due to competitive advantage concerns) is needed to provide more confidence in the comparisons between training and match play T_c. Similarly, replication studies across a range of different ambient WBGT temperatures will strengthen our understanding through a more robust assessment of the independent effects of additional clothing interventions, and standardised comparisons of training to available match T_c data. The magnitude of T_c response (see Figure 5.1) demonstrated some individual variability (see Figure 5.2), which practitioners should consider when physical preparation strategies for hot and humid competitions are being considered/prescribed. Finally, practitioners are advised to follow practices that ensure interventions such as those described in this study are performed in the safest possible manner. These include prior medical screening, gradual progression of thermal strain, having hydration available, close supervision and support, and regular evaluation and assessment of responses within and between sessions.

PRACTICAL APPLICATIONS

- Wearing additional clothing (compression garments and full tracksuit) during rugby sevens training is an accessible and valid method to achieve increased T_c and perceived exertion; without negatively affecting external locomotive output or compromising training specificity.

CONCLUSIONS

Elite female rugby sevens athletes generate high T_c when competing [peak T_c median (range) when involved in > 6 min match play: 39.3°C (38.2 – 39.8°C)] in temperate conditions (Henderson et al. 2020). This study showed that when training is performed in hot environments, player T_c reflects the magnitudes experienced when involved in > 6 min of match play in temperate conditions. Further, previous approaches to HA have experienced limited adoption due to logistical and financial obstacles in elite team sports. This research has found additional clothing to be a viable and effective method to increase heat strain in elite female rugby sevens players without introducing undesirable EHI-associated pathologies or compromising training specificity / external locomotive capacity. These findings provide evidence to rugby sevens practitioners tasked with preparing athletes for the thermal demands of the sport; and provide practitioners with an accessible, evidence-based tool to help deliver a physical thermal load associated with the procurement of a HA phenotype, but further confirmatory work is required to strengthen these initial findings.

CHAPTER 6 | LIMITING RISE IN HEAT-LOAD WITH AN ICE-VEST DURING ELITE FEMALE RUGBY SEVENS WARM-UPS

Henderson, M.J., Chrismas, B.C.R., Stevens, C.J., Fransen, J., Coutts, A.J. & Taylor, L. (2020). Limiting rise in heat-load with an ice-vest during elite female rugby sevens warm-ups. International Journal of Sports Physiology & Performance, 16(11): 1684 – 1691.

ABSTRACT

Purpose: To determine the effect of wearing a phase-change cooling vest on elite female rugby sevens athletes during (1) a simulated match day warm-up in hot conditions prior to a training session; and (2) a pre-match warm-up during a tournament in cool conditions. **Methods:** This study consisted of two randomised independent group designs (separated by 16 days) where athletes completed the same 23 – 25 min match-day warm-up (1) in hot conditions (range: 28.0 – 35.1°C wet bulb globe temperature [WBGT]) prior to training, and (2) in cool conditions (range: 18.8 – 20.1°C WBGT) prior to a World Rugby Women's Sevens Series match. In both conditions, athletes were randomly assigned to wear either: (i) the standardised training/playing ensemble (synthetic rugby shorts and training tee/jersey); or (ii) the standardised training / playing ensemble plus a commercial phase-change athletic cooling vest. Group-wise differences in T_c rise from baseline, GPS-measured external locomotive output and perceptual thermal load were compared. **Results:** T_c rise during a match warm-up was lower in the hot condition only when wearing an ice vest [-0.65°C (95% CI = -1.22 – -0.08°C), η_p^2 = 0.23 (95% CI = 0.00 – 0.51), p = .028]. No differences in various external load variables were observed between conditions. **Conclusions:** Phase change cooling vests can be worn by athletes prior to, and during, a pre-match warm-up in hot conditions to limit excess T_c rise without adverse effects on thermal perceptions or external locomotion output.

INTRODUCTION

Exercise in thermally challenging environments increases physiological and perceptual strain on athletes, compromising physical (Cheung & Sleivert 2004), technical (Sunderland & Nevill 2005), and cognitive performance (Martin et al. 2019) within endurance (Nybo, Rasmussen & Sawka 2014) and repeat sprint (Girard, Brocherie & Bishop 2015) exercise. Long-term (≥14 days) heat acclimation/acclimatisation protocols provide the greatest protection against hyperthermia-mediated physical performance decrements and exertional heat illnesses (Racinais, Alonso, et al. 2015). However, logistical and financial barriers often prevent practitioners from implementing ecologically valid, evidence-based interventions in team sports settings (Casadio et al. 2017). Match-/race-day pre-cooling represents a short-term strategy able to improve intermittent [Cohen's *d* (95% CI) = 0.47 (0.40 – 0.53)] and prolonged [Cohen's *d* (95% CI) = 2.04 (1.53 – 2.36)] physical performance in hot environments (Tyler, Sunderland & Cheung 2015) and slow the rate of core body temperature increase towards higher end temperatures (Taylor, Stevens, et al. 2019).

The WRWSS is the premier women's international rugby sevens series/competition, with successful match outcomes requiring a unique integration of physical capacities and technical skill execution (Ross, Gill & Cronin 2015). Match demands include average speeds of 86 ± 4 $m \cdot min^{-1}$ (with 11 ± 3% performed >5 $m \cdot s^{-1}$), maximum speeds of 8.05 ± 0.55 $m \cdot s^{-1}$, maximum accelerations of 3.49 ± 0.38 $m \cdot s^{-2}$, and 12.6 ± 4.7 impacts greater than 10 g (Clarke, Anson & Pyne 2017). These demands have been shown to elicit high T_c (37.9 – 39.8°C), even in temperate conditions [18.9 – 20.1°C wet bulb globe temperature (WBGT)] (Henderson et al. 2020), but T_c data from match-play in hot conditions is not currently available. Pre-cooling using a phase-change ice vest has demonstrated favourable alterations in physiological and perceptual warm-up responses in warm conditions [23 – 27°C (Taylor, Stevens, et al. 2019)] in elite men's rugby sevens (Clarke, Anson & Pyne 2017), however, the dose used (70 minutes before warm-up) may not always be implementable in practice. Phase change materials provide an efficient and effective means of cooling by leveraging the energy-absorbing and energy-releasing capabilities during their phase transitions (Sharma et al. 2009). In addition to being used for cooling garments, phase change materials have been applied in temperature regulation for buildings and homes (Faraj et al. 2020) and thermal management for electronics (Kandasamy, Wang & Mujumdar 2008) among many applications. No pre-cooling data from female rugby sevens athletes currently exists despite potentially being of greater concern (and more effective) due to between-sex differences in athlete anthropometrics (Clarke, Anson & Pyne 2017) and reproductive physiology/endocrinology (Giersch et al. 2020) influencing thermoregulation (Kaciuba-Uscilko & Grucza 2001). Considering the high T_c observed in temperate match-play (Henderson et al. 2020) is theoretically capable of reducing the physical performance (Girard, Brocherie & Bishop 2015), other hotter tournaments of the WRWSS (e.g. Dubai, Hong Kong; commonly >30°C) and the Tokyo Olympic Games [~30°C WBGT (Kakamu et al. 2017)] may challenge practitioners to manage athlete body temperatures to facilitate heightened performance.

This study aims to determine the effect of wearing a phase-change cooling vest [worn for a reduced duration before warm-up than previously investigated (< 15 min vs 70 min (Taylor, Stevens, et al. 2019))] within elite female rugby sevens athletes during (1) a simulated match day warm-up in hot conditions (range: 28.0 – 35.1°C WBGT) prior to a training session; and (2) a pre-match warm-up during a tournament in cool conditions (range: 18.8 – 20.1°C WBGT). It is hypothesised that (i) athletes wearing the vest will experience a decreased rise in T_c from baseline to peak (ΔT_c) in both warm-ups; (ii) without significant differences in global positioning systems (GPS) measured external load during either; and (iii) shorter exposure time to pre-cooling [e.g., < 15 min vs 70 min (Taylor, Stevens, et al. 2019)] will not meaningfully change the magnitude of observed T_c effects.

METHODS

SUBJECTS

Data were collected from a total of 17 seasonally heat-acclimatised female athletes (see Table 6.1 for details) from a single 2018-19 WRWSS team based in Sydney, Australia. The full population of professionally contracted international female rugby sevens athletes in the country, available to play at the time of data collection, were recruited (with only the match-day squad available on match-day). Written informed consent was provided for the project under ethical approval from the Southern Cross University (ECN-

18-216) and the University of Technology Sydney (ETH19-4051) Human Research Ethics Committees in the spirit of the Helsinki Declaration.

Table 6.1 Player characteristics, anthropometry, and body composition. Data are presented as median (minimum – maximum).

	TRAINING$_{HOT}$		**TOURNAMENT$_{COOL}$**	
	CON	**VEST**	**CON**	**VEST**
Age (y)	23 (17 – 30)	24 (19 – 29)	25 (18 – 30)	21 (19 – 25)
Height (m)	169.1 (165.0 – 172.0)	169.5 (164.5 – 173.8)	168.9 (164.5 – 173.8)	169.95 (167 – 172)
Body mass (kg)	69.2 (63.9 – 77.7)	68.8 (59.2 – 74)	68.8 (65.4 – 77.7)	67.4 (59.2 – 74)
Sum SF (mm)	63.9 (43.6 – 84.3)	70.1 (38.9 – 82.5)	62.9 (55.4 – 73.5)	65.0 (38.9 – 71.7)
Triceps SF (mm)	6.3 (4.5 – 10.1)	6.8 (3.8 – 11.8)	6.5 (4.8 – 7.7)	6.1 (3.8 – 8.4)
Subscapular SF (mm)	8.6 (5.6 – 13.5)	9.4 (6.5 – 15.2)	8.9 (7.5 – 15.2)	8.8 (5.6 – 10.5)
Bicep SF (mm)	3.9 (3.2 – 6.0)	4.2 (2.9 – 6.7)	3.9 (3.8 – 6.7)	4.0 (2.9 – 6.0)
Supraspinale SF (mm)	8.0 (3.8 – 11.3)	8.2 (5.2 – 16.8)	7.5 (5.8 – 16.8)	7.5 (4.6 – 11.6)
Abdomen SF (mm)	11.4 (4.1 – 13.6)	11.7 (8.7 – 20)	11.2 (9.8 – 15.0)	11.1 (4.1 – 20.0)
Thigh SF (mm)	16.9 (14.8 – 25.4)	17.2 (8.5 – 26)	15.0 (10.4 – 23.0)	17.4 (8.5 – 20.9)
Calf SF (mm)	7.7 (3.8 – 12.0)	9.1 (3.0 – 12.0)	8.1 (4 – 9.3)	7.5 (3.0 – 10.8)
Body fat (%)	19.7 (13.2 – 21.9)	19.1 (14.7 – 25.4)	18.7 (16.2 – 25.4)	17.8 (13.2 – 21.3)
LBM (kg)	55.7 (49.9 – 62.5)	54.9 (49.8 – 63.1)	56.1 (51.8 – 62.5)	51.3 (49.8 – 63.1)

SF = skinfold; LBM = lean body mass

DESIGN

The research design consisted of two randomised independent group designs (separated by 16 days):

(1) TRAINING$_{HOT}$: All athletes (n = 16) simultaneously complete the same 23 – 25 min simulated match day warm-up before a training session [range: 28.0 – 35.1°C WBGT (SD-2010, Reed Instruments, NC, USA)].

(2) TOURNAMENT$_{COOL}$: All athletes (entire team; n = 12) simultaneously complete the same (see TRAINING) 23 – 25 min pre-match warm-up on a WRWSS tournament day (range: 18.8 – 20.1°C WBGT).

In both $TRAINING_{HOT}$ and $TOURNAMENT_{COOL}$ conditions, athletes were randomly assigned to wear either: (i) the standardised training / playing ensemble [synthetic rugby shorts and training tee/jersey; $TRAINING_{HOTCON}$ (n = 8) or $TOURNAMENT_{COOLCON}$ (n = 6)]; or (ii) the standardised training / playing ensemble plus a commercial phase-change athletic cooling vest (TechNiche Hybrid Cooling Vest Product 4531; TechNiche International, California, USA) worn for no longer than 15 minutes before the warm-up commencing [$TRAINING_{HOTVEST}$ (n = 8; worn for 14 minutes prior) or $TOURNAMENT_{COOLVEST}$ (n = 6; worn for only 6 minutes prior due to tournament logistical constraints)]. The phase change cooling material was applied to both anterior and posterior sides of the torso. The warm-up consisted of intermittent bouts of high-intensity accelerations, decelerations, and rugby specific skills (catching, passing, tackling). Athletes had been in the same time zone ≥14 days prior to the training session/match, thus circadian misalignment in T_c was not a confounding influence. Menstrual cycle was unable to be determined within this cohort as it is not controlled by the medical staff, rather it is the protocol within this team that the athletes have the right to manage their menstrual cycle as they see fit.

METHODOLOGY

Athletes ingested an e-Celsius™ telemetric capsule (BodyCap, Caen, France) the night prior to $TRAINING_{HOT}$/$TOURNAMENT_{COOL}$. T_c data was only included within the statistical model when ≥5 hours had elapsed post-ingestion, a criterion used previously to ensure the capsule was in the lower intestine (Byrne & Lim 2007; Henderson et al. 2020; Taylor, Stevens, et al. 2019; Taylor, Thornton, et al. 2019). Baseline T_c was obtained from a stable 30-minute period (e.g., T_c ± 0.1) upon waking. T_c was sampled at 30 s intervals, with data downloaded at the end of the training session/match via a wireless data receiver (e-Viewer, BodyCap, Caen, France). Capsules were prepared, calibrated, and handled as outlined previously (Henderson et al. 2020; Taylor, Stevens, et al. 2019; Taylor, Thornton, et al. 2019; Travers et al. 2016). The e-Celsius™ system has been determined valid and reliable for intermittent-running exercise (Travers et al. 2016), as well as shown excellent validity (ICC 1.00), test-retest reliability (ICC 1.00), and inertia in water bath experiments between 36°C and 44°C (Bongers et al. 2018). The e-Celsius™ system has also been used previously within elite rugby sevens matches (Henderson et al. 2020;

Taylor, Thornton, et al. 2019) and training (Henderson et al. 2021; Taylor, Stevens, et al. 2019).

Activity profiles in $TRAINING_{HOT}$ were measured using 10 Hz GPS devices (EVO, GPSports, Canberra, Australia). These have shown good inter-unit reliability for distance (m; CV: 0.2 ± 1.5%), average speed ($m \cdot min^{-1}$; CV: 0.2 ± 1.5%), max velocity ($m \cdot s^{-1}$; CV: 0.2 ± 1.5%), high-speed running (distance covered > 5 $m \cdot s^{-1}$; CV: 0.5 ± 1.5%), and average acceleration/deceleration ($m \cdot s^{-2}$; CV: 1.2 ± 1.5%) (Thornton et al. 2019). Each unit was assigned to an individual athlete and worn underneath their training shirt in a small upper-body garment custom designed by the device manufacturer, positioning the unit between the scapula blades of the athlete. Following the session, stored data were downloaded from the devices using the manufacturer's proprietary software (GPSports Console, GPSports, Canberra, Australia). Metrics exported from the GPS data included training duration (min), average speed ($m \cdot min^{-1}$), high-speed running per minute ($HSR \cdot min^{-1}$; average distance per min covered > 5 $m \cdot s^{-1}$), very high-speed running per minute ($VHSR \cdot min^{-1}$; average distance per min covered > 6 $m \cdot s^{-1}$), and average absolute acceleration/deceleration (Ave acc/dec; in metres per second squared). External load data was not able to be collected in $TOURNAMENT_{COOL}$ due to tournament day timing and logistical constraints meaning the devices were required in the holding area, where the signal could be acquired and retained for match-play purposes, as match-play data took priority over warm-up data.

Thermal sensation (TS) was measured using a 17-point category ratio scale (where 0 = 'unbearably cold' and 8 = 'unbearably hot') (Young et al. 1987). Thermal comfort (TC) was measured using a 10-point ordinal scale (where 1 = 'comfortable' and 10 = +1 above 'extremely uncomfortable') (Borg 1982). Both TS and TC represent how athletes were feeling when asked (i.e., not a session average). Due to tournament constraints, collecting TS and TC in $TOURNAMENT_{COOL}$ was not possible. As a result, TS and TC are only available in $TRAINING_{HOT}$.

All measures were obtained as per Figure 6.1, by the same practitioners using standardised language and procedures.

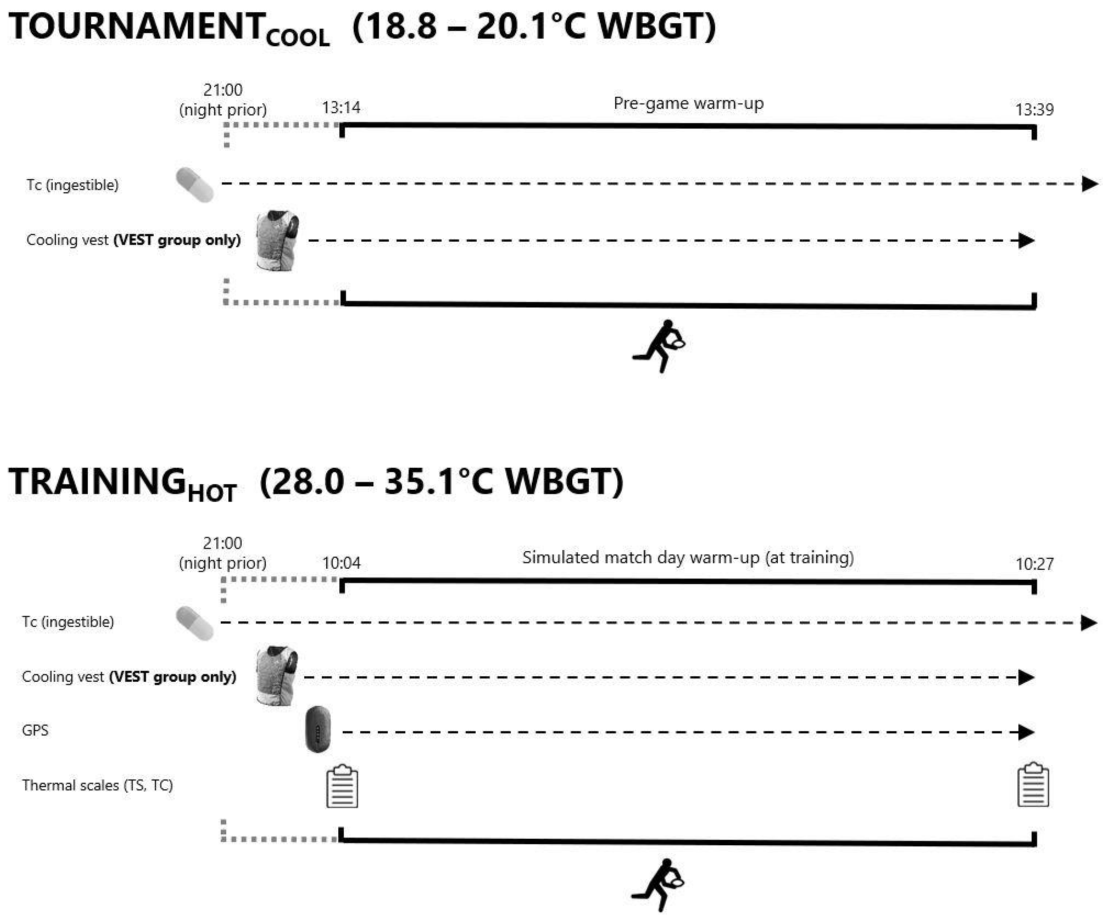


Figure 6.1 Experimental schematic. Tc = core temperature (ingestible telemetric pill); GPS = Global Positioning Systems; TS = thermal sensation; TC = thermal comfort.

STATISTICAL ANALYSES

All statistical analyses were performed, and figures were created, using R statistical software (R Core Team 2022). Descriptive statistics are reported as median and range (min – max) unless otherwise stated. Individual athlete T_c was collected and averaged for each warm-up, with peak T_c values extracted and individual athlete change from the baseline calculated.

Core temperature: A linear mixed model was fitted using the {lme4} package (Bates et al. 2015) to determine the effect of pre-cooling using a phase-change cooling vest, and environmental conditions (i.e. TRAINING$_{HOT}$/TOURNAMENT$_{COOL}$), on ΔT_c during a warm-up. The experimental group (TRAINING$_{HOTCON/VEST}$ or

$TOURNAMENT_{COOLCON/VEST}$) and conditions ($TRAINING_{HOT}$ or $TOURNAMENT_{COOL}$) were entered into the model as fixed effects (with interaction). Random intercepts for each athlete were included to account for repeated measures and individual variance. P-values were obtained by Kenward-Roger approximation (Kenward & Roger 1997) which has been shown to produce acceptable Type 1 error rates, even for smaller samples (Luke 2017). Pseudo 'variance explained' (R^2) values were calculated (Nakagawa & Schielzeth 2013) to assess model goodness-of-fit. Approximate partial eta squared effect sizes (η_p^2) were converted from test statistics and degrees of freedom using the {effectsize} R package (Ben-Shachar, Makowski & Lüdecke 2020). Both goodness-of-fit (R^2: 0.02 = *weak*, 0.13 = *moderate*, 0.26 = *substantial*) and effect sizes (η_p^2: *small* = 0.01, *medium* = 0.06, *large* = 0.14) were interpreted using Cohen's recommendations (Cohen 1988).

External load: A multivariate analysis of variance (MANOVA) was performed on GPS-measured external load metrics (dependent variables: $m{\cdot}min^{-1}$, $HSR{\cdot}min^{-1}$, $VHSR{\cdot}min^{-1}$, and Ave acc/dec) to investigate potential differences in locomotion related to wearing the cooling vest (independent variable: experimental group). Assumptions of homogeneity and multivariate normality were checked using Box's Homogeneity of Covariance Matrices Test and Shapiro-Wilk Multivariate Normality Test, respectively.

Perceptual measures: As TS and TC are ordinal variables, it would be inappropriate to make statistical inferences from tests requiring a continuous dependent variable (despite similar data sets using an array of these approaches previously (Périard et al. 2014b; Stephens, Argus & Driller 2014)). To perform the appropriate ordinal regression on this data, a larger sample would be required and is likely not possible with one rugby sevens team using a 17-point (TS) and 10-point (TC) scale. Therefore, TS and TC are provided as a central tendency (median) and dispersion (range) (see Figure 6.3) and discussed only in raw unit changes/comparisons; this approach has been used elsewhere (Henderson et al. 2021).

RESULTS

Raw data for ΔT_c and external load for all athletes are presented in Tables 6.2 and 6.3.

Table 6.2 Core body temperature descriptive statistics between conditions and experimental groups. Data are presented as median (range) for all players.

Condition		Group	Core temperature (°C)	Change from baseline (°C)
$TOURNAMENT_{COOL}$ (18.8 – 20.1°C WBGT)	*Baseline*	Control (no cooling vest)	37.2 (37.1 – 37.4)	
		Intervention (cooling vest)	37.2 (37.0 – 37.5)	
	Mean	Control (no cooling vest)	38.1 (37.4 – 38.5)	0.8 (0.2 – 1.2)
		Intervention (cooling vest)	38.3 (37.4 – 38.5)	1.0 (0.1 – 1.5)
	Peak	Control (no cooling vest)	38.4 (38.1 – 39.0)	1.1 (0.8 – 1.7)
		Intervention (cooling vest)	38.7 (37.9 – 38.9)	1.4 (0.6 – 1.9)
$TRAINING_{HOT}$ (28.0 – 35.1°C WBGT)	*Baseline*	Control (no cooling vest)	36.9 (36.7 – 37.2)	
		Intervention (cooling vest)	37.2 (37.0 – 37.4)	
	Mean	Control (no cooling vest)	37.9 (37.8 – 38.1)	0.9 (0.9 – 1.2)
		Intervention (cooling vest)	38.1 (37.5 – 38.3)	0.9 (0.3 – 1.2)
	Peak	Control (no cooling vest)	38.4 (38.2 – 38.7)	1.4 (1.3 – 1.8)
		Intervention (cooling vest)	38.4 (37.9 – 38.7)	1.2 (0.7 – 1.6)

WBGT: Wet bulb globe temperature

Table 6.3 Global Positioning Systems (GPS) measures between experimental groups during the simulated match day warm-up prior to training. Data are presented as median (range) for all players.

Group	$m \cdot min^{-1}$	$HSR \cdot min^{-1}$	$VHSR \cdot min^{-1}$	Ave acc/dec
CON	59.3 (53.8 – 67.1)	5.1 (4.0 – 5.9)	2.4 (1.2 – 3.3)	0.36 (0.32 – 0.38)
VEST	60.4 (55.7 – 61.1)	4.3 (2.7 – 6.0)	2.5 (0.2 – 3.5)	0.36 (0.30 – 0.39)

$m \cdot min^{-1}$: metres per minute; $HSR \cdot min^{-1}$: metres per minute covered at greater than 5 metres per second; $VHSR \cdot min^{-1}$: metres per minute covered at greater than 6 metres per second; Ave acc/dec: average acceleration/deceleration in $m \cdot s \cdot s^{-2}$.

Core temperature: The effect of wearing a cooling vest during a warm-up on ΔT_c in hot or cool conditions is presented in Figure 6.2 and Table 6.4. The model's total explanatory power is *substantial* (conditional R^2 = 0.45; i.e., this model explains 45% of the variance in ΔT_c) and the part related to the fixed effects alone (marginal R^2; excluding variation between athletes) is 0.23. Within this model:

- The main effect of hot conditions (28.0 – 35.1°C WGBT), controlling for the experimental group, resulted in a 0.41°C greater ΔT_c and can be considered *large* and significant (η_p^2 = 0.22, p = .042).

- The main effect of wearing the cooling vest, controlling for hot or cool conditions, resulted in a 0.27°C greater ΔT_c and can be considered as *medium* and not significant (η_p^2 = 0.06, p = .275).

- The interaction effect of hot conditions (28.0 – 35.1°C WGBT), combined with wearing the cooling vest, resulted in a -0.65°C lesser ΔT_c (i.e., the effect of hot conditions on ΔT_c is limited by wearing a cooling verst) and can be considered as *large* and significant (η_p^2 = 0.23, p = .028).

Visual inspection of diagnostic plots did not reveal any obvious deviations from normality, and the Shapiro-Wilk test performed on the model residuals suggested no evidence of non-normality (p = .786).

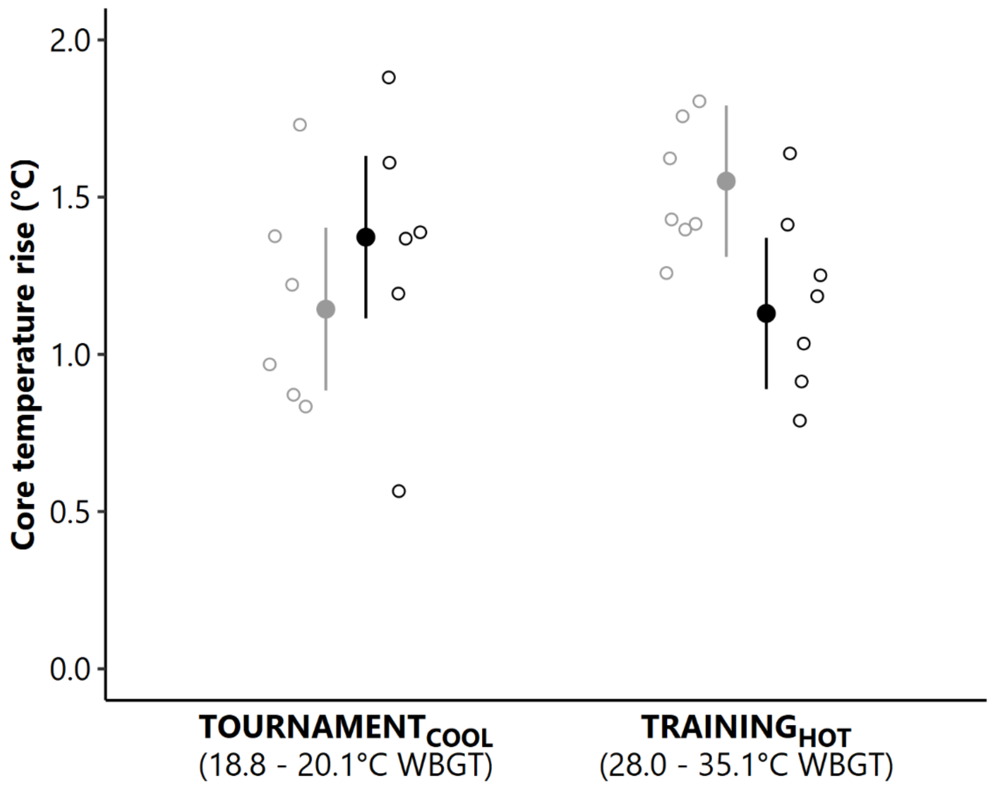


Figure 6.2 Individual rise in core temperature (baseline to peak) for TOURNAMENT$_{COOL}$ and TRAINING$_{HOT}$. Filled circles represent predicted group means from a linear mixed model, lines represent a 95% confidence interval of the predicted group means, and unfilled circles represent individual data for VEST (black) and CON (grey) conditions.

Table 6.4 Linear mixed-effects model assessing the effect of experimental group and conditions (with interaction) on the rise in core temperature during a warm-up.

Predictors	**Estimates (95% CI)**	**std. Error**	**t**	**df**	**p**	**η_p^2 (95% CI)**	**ES interpretation**
(Intercept)	1.14 (0.85 – 1.44)	0.14	8.11	21.66	**< 0.001**		
Conditions							
TOURNAMENT$_{COOL}$ (18.8 – 20.1°C WGBT)				*Reference*			
TRAINING$_{HOT}$ (28.0 – 35.1°C WGBT)	0.41 (0.02 – 0.80)	0.18	2.20	16.78	**0.042**	0.22 (0.00 – 0.52)	*large*
Group							
CON				*Reference*			
VEST	0.23 (-0.20 – 0.65)	0.20	1.12	19.85	0.275	0.06 (0.00 – 0.33)	*medium*
Interaction							
TRAINING$_{HOTVEST}$	-0.65 (-1.22 – -0.08)	0.27	-2.37	19.08	**0.028**	0.23 (0.00 – 0.51)	*large*
N $_{Player}$				17			
Observations				26			
Marginal R^2 / Conditional R^2				0.231 / 0.452			

CI: confidence interval; *df*: degrees of freedom; η_p^2: approximate partial eta squared; *ES*: effect size

External load: No differences in external load between experimental groups were found [$F_{(4, 11)} = 0.26$, $p = .898$, η_p^2 (95% CI) = 0.09 (0.00 – 0.24), Wilk's Λ = 0.914)]. Despite the Shapiro-Wilk test observing a multivariate non-normal distribution of errors, violations of this assumption within linear models are rarely problematic; particularly when univariate error distributions do not violate normality assumptions to the same extent (as is the case here). The commonly recommended solutions to this problem (e.g. using non-parametric tests, and generalised linear models) have been suggested to represent a greater threat to the reliability of conclusions because of their lower flexibility or robustness (Knief & Forstmeier 2018). Observed covariance matrices were homogenous across groups ($p = .082$).

Perceptual measures: Raw unit increase in TS was 2.0 (1.0 – 2.5) in CON and 2.0 (-1.5 – 2.0) in VEST. A raw unit increase in TC was 2.5 (1.0 – 3.0) in VEST and 3.0 (1.0 – 4.0) in CON.

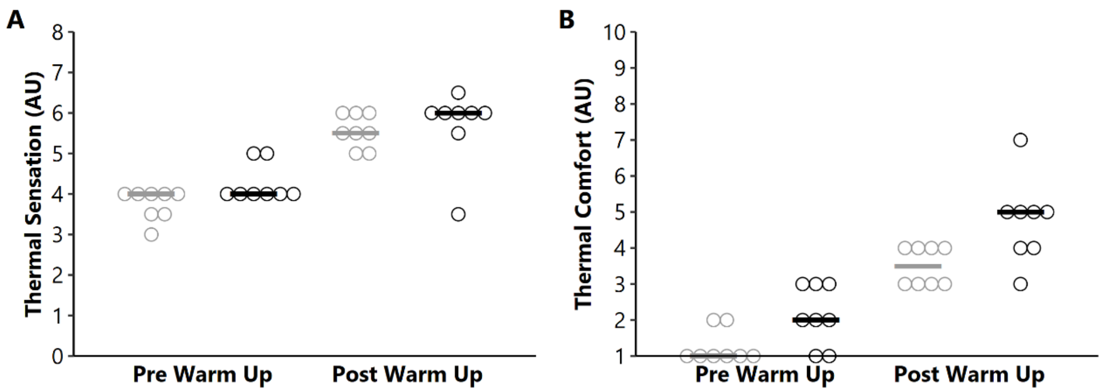


Figure 6.3 Individual pre- and post-warm-up thermal sensation (3A) and thermal comfort (3B) for all players. Solid horizontal lines represent the group median and circles represent individual data for VEST (black) and CON (grey) conditions. AU = arbitrary units.

DISCUSSION

Warm-up ΔT_c was decreased by wearing a phase-change cooling vest in the $\text{TRAINING}_{\text{HOT}}$ condition (-0.65°C, $\eta_p^2 = 0.23$, $p = .028$), but not in the $\text{TOURNAMENT}_{\text{COOL}}$ condition. This rejects experimental hypothesis (i) theorising a uniform decrease across conditions. No differences were observed in GPS-measured external load metrics as a result of wearing the phase-change cooling vest in support of hypothesis (ii). Reduced duration of phase-change cooling vest wear prior to warm-up in hot conditions (< 15 min), compared to comparable men's rugby sevens data (70 min) (Taylor, Stevens, et al. 2019), maintained similar decreases in ΔT_c compared to their respective control conditions [-0.65°C in present study vs -0.70°C (Taylor, Stevens, et al. 2019)] in support of hypothesis (iii).

Although short-term (<30 s) power output or single-sprint performances can be enhanced from higher temperatures (largely due to improved muscle contractility), poorer intermittent-sprint performances are observed in hot conditions when exercise induces marked hyperthermia (Girard, Brocherie & Bishop 2015). Extending the time before athlete T_c exceeds the hyperthermic 'tipping point' [suggested to be 39°C (Girard, Brocherie & Bishop 2015)] in a match [compromising central nervous system function (Girard, Brocherie & Bishop 2015), repeat sprint ability (Drust et al. 2005; Girard, Brocherie & Bishop 2015), and intermittent sprint performance (Sunderland & Nevill 2005)] has been suggested to benefit physical performance capacity (Taylor, Stevens, et al. 2019). The strategy of starting a match with a lower T_c through a pre-cooling intervention (i.e., a T_c heat sink) may delay these adverse physical effects of hyperthermia (Taylor, Carter & Stellingwerff 2020). The effect of the phase-change cooling vest decreasing ΔT_c in $\text{TRAINING}_{\text{HOT}}$, but not $\text{TOURNAMENT}_{\text{COOL}}$, in this study may be explained by the higher ambient temperatures (28.0 – 35.1°C WGBT) in the former condition (i.e., unbalancing of the conceptual heat balance equation in favour of heat gain, through the combination of exercise heat production and gain from the environment in $\text{TRAINING}_{\text{HOT}}$ compared $\text{TOURNAMENT}_{\text{COOL}}$). Specifically, when the cooling vest is worn (introducing conductive heat loss), heat gain is slowed in the hotter ambient conditions ($\text{TRAINING}_{\text{HOT}}$). In the cooler ambient conditions ($\text{TOURNAMENT}_{\text{COOL}}$), the combination of radiant heat from the environment and exercise heat production did not appear to be sufficient for the conductive cooling properties of the vest to be realised or effective to T_c.

A common concern among coaches in elite sports is the reluctance to introduce any untested and non-athlete-familiarised elements to their preparation, that could potentially disturb or prevent athletes from performing optimally. Whilst there were limited components to the match warm-up with internally governed locomotion, wearing the phase-change cooling vest did not result in differences in GPS-measured external output compared to control. This objectively supports the notion that these commercially available garments (manufactured to suit athletic activity and populations) did not prevent normal movement requirements of a match warm-up. Further support is found in elite men's rugby sevens data (Taylor, Stevens, et al. 2019), with similar countermovement jump performance improvement observed following warm-up, irrespective of wearing a phase-change cooling vest (~5 cm; Cohen's $d = 0.29 \pm 0.11$). Subjectively, athletes reported that wearing the vest was not uncomfortable nor did it impede their ability to fully engage with or execute any aspect of the warm-up. Despite this, ambient temperature largely influenced athletes' enthusiasm for wearing the garment, with athletes actively seeking them in the $\text{TRAINING}_{\text{HOT}}$ condition but notably reluctant in the $\text{TOURNAMENT}_{\text{COOL}}$ condition.

Elite rugby sevens tournaments challenge practitioners to optimise athlete preparation within narrow externally imposed windows of time (warm-ups, matches, access to facilities, etc.) and staffing constraints (e.g., externally imposed number of staff per tournament). The only available data on warm-up T_c responses using a phase-change cooling vest in elite rugby sevens was from male athletes who wore the garments for 70 minutes prior to their warm-up (simulated prior to training) (Taylor, Stevens, et al. 2019). Whilst this dosage was effective, the duration is likely to be logistically problematic for practitioners tasked with the physical preparation of rugby sevens athletes, on tournament day between matches, due to competing time demands (e.g., preparing nutrition/hydration, planning/preparing warm up/recovery etc.). The present study has shown that beneficial effects can still be obtained from shorter duration phase-change cooling vest use (15 min prior to warm-up) in hot conditions when a reduced T_c post-warm-up and pre-match (e.g., a T_c heat sink) may be desired. This evidence enables practitioners to experiment with shorter durations of vest wear before warm-ups without sacrificing effectiveness, and thus present a reduced burden for time-poor practitioners and athletes.

The findings of the present study are limited by the restricted sample of elite female rugby sevens athletes available to participate (n = 17). However, this sample represented the full population of professionally contracted international female rugby sevens athletes in the country that were available (in $TRAINING_{HOT}$) or the full match-day squad ($TOURNAMENT_{COOL}$) at the time of data collection. Further, the lower environmental temperature (18.8 – 20.1°C in $TOURNAMENT_{COOL}$ vs 28.0 – 35.1°C in $TRAINING_{HOT}$) and duration (6 minutes in $TOURNAMENT_{COOL}$ vs 14 minutes in $TRAINING_{HOT}$) of ice-vest wear prior to the start of the warmup is likely to have influenced the cooling effect of the phase change material. The magnitude of T_c responses demonstrated some individual variability (see Figure 6.2), which practitioners should account for when planning individualised interventions. Future research should seek to employ a crossover design from a larger sample (evidently difficult in elite rugby sevens) to better control for variance in individual thermoregulatory responses.

PRACTICAL APPLICATIONS

- Phase change cooling vests can be worn by athletes prior to, and during, a pre-match warm-up in hot conditions to limit excess ΔT_c without adverse effects on thermal perceptions or external locomotion output.
- Practitioners can experiment with shorter durations of wear (< 15 min before warm-up) for a similar benefit and reduced time burden (compared to prior data in elite males).

CONCLUSION

The high T_c observed during match-play in elite female rugby sevens athletes (Henderson et al. 2020) surpasses magnitudes theorised to negatively affect physical performance capacity (Girard, Brocherie & Bishop 2015). This study showed efficacy for phase-change cooling vest use prior to, and during, the warm-up to limit within and post-warm-up ΔT_c, compared to control, when performing in hot conditions (without adverse effects on thermal perceptions or external locomotion output). Similarly, this research showed that the previously investigated prolonged durations of wear prior to warm-up (Taylor, Stevens, et al. 2019) may not be necessary for beneficial effects. These findings provide evidence to rugby sevens practitioners tasked with acutely preparing athletes for the thermal demands of the sport; and provide practitioners with an accessible, evidence-based method to limit excessive pre-match ΔT_c (and associated negative effects). Further confirmatory work with a larger sample is required to strengthen these initial findings.

CHAPTER 7 | RESPONSES TO A 5-DAY SPORT-SPECIFIC HEAT ACCLIMATISATION CAMP IN ELITE FEMALE RUGBY SEVENS ATHLETES

Henderson, M.J., Chrismas, B.C.R., Fransen, J., Coutts, A.J. & Taylor, L. (2022). Responses to a 5-day sport-specific heat acclimatisation camp in elite female rugby sevens athletes. *International Journal of Sports Physiology & Performance*, 17(6): 969 – 978.

ABSTRACT

Purpose: Describe the physiological (resting T_c, exercising heart rate, sweat rate) and psychophysical (rating of perceived exertion, thermal sensation, thermal comfort) responses to a short-term heat acclimatisation (HA) training camp in elite female rugby sevens athletes. **Methods:** Nineteen professional female rugby sevens athletes participated in a 5-day HA camp in Darwin, Australia (training average: 32.2°C and 58% relative humidity). The training involved normal team practice prescribed by appropriate staff. Markers of physiological and psychophysical adaptations to HA were collected at various stages during the camp. Partial eta squared effect sizes (from linear mixed effects models), rank-biserial correlations (from Freidman tests), and *p*-values were used to assess changes across the protocol. **Results:** Resting T_c did not significantly change. Exercising heart rate showed a large and significant reduction from day 1 to day 5 (175 ± 13 vs 171 ± 12 bpm), as did sweat rate (1.1 ± 0.3 vs 1.0 ± 0.2 $L \cdot h^{-1}$). Thermal sensation showed a large and significant reduction between day 1 and day 5 (median [IQR] = 5 [5 – 5.5] vs 4.5 [4 – 5]). Changes in the rating of perceived exertion and thermal comfort were unclear. **Conclusions:** Beneficial cardiovascular adaptations were observed simultaneously across a full squad of elite female rugby sevens players (without expensive facilities/equipment or modifying training content). However, beneficial changes in resting T_c, sweat rate, and thermal/effort perceptions likely require a greater thermal impulse. These data contribute to the development of evidence-informed practice for minimal effective HA doses in female team sport athletes, who are underrepresented in the current research.

INTRODUCTION

Appropriately prescribed and regular exposure to hot conditions during a training period promotes positive physiological and psychophysical adaptations beneficial to subsequent performance in the heat (Daanen, Racinais & Périard 2018; Tyler et al. 2016). Such adaptations include enhanced cardiovascular (Kissling, Akerman & Cotter 2020) and thermoregulatory (Tyler et al. 2016) capacities, as well as favourably-altered perceptions of heat and exertion (Flouris & Schlader 2015). Consensus recommendations on training and competing in the heat advise that heat acclimation (artificial heat) or acclimatisation (natural heat) protocols (HA) comprise repeated heat exposures over 1 – 2 weeks to obtain a fully-acclimated phenotype. Despite this, early adaptations such as lowered T_c and exercise heart rate (HRex) can be obtained in as little as a few days (Racinais, Alonso, et al. 2015). Whilst prolonged HA protocols are understood to be the most effective in achieving the desired outcomes, team sports practitioners seeking heat adaptations for their athletes are often challenged by: (1) large athlete numbers; (2) limited or no access to equipment/facilities for procuring HA adaptations (e.g., heat chamber) or monitoring responses (e.g., specialist equipment to assess plasma volume expansion); (3) training specificity / interference effect concerns; (4) congested fixture and travel schedules; and (5) time constraints around technical/tactical training. Pragmatism is required when planning and implementing interventions within these constraints. Protocols that can be performed without sacrificing training specificity or requiring expensive facilities/equipment will be highly regarded. Addressing these concerns, shorter HA options that are viable for a large group, whilst retaining some benefits associated with more comprehensive protocols, will be of value to practitioners working in elite team sport contexts.

Research regarding heat training adaptations has mostly focused on males, limiting applicability to female athletes (Giersch et al. 2020; Hutchins et al. 2021; Kirby et al. 2021). This limited available evidence suggests females require a stronger HA dose (e.g., longer HA period, greater heat stress, more sessions) to achieve comparable adaptation to males (Wickham, Wallace & Cheung 2020). Although unclear, methodological discrepancies have been suggested as potentially explaining a lower thermal strain being experienced by females for a given thermal stress. Differences in anthropometry, training status, environmental conditions, or reduced T_c during the follicular phase of the menstrual cycle, may account for the lower thermal heat strain (Wickham, Wallace & Cheung 2020). In sports, these differences commonly surface as female athletes possessing a smaller body mass, higher surface area to volume ratio, and reduced absolute exercise capacity (all increasing heat loss capacity), whilst also possessing higher body fat content and less muscle mass (decreasing heat storage capacity) when compared to males of a similar level (Wickham, Wallace & Cheung 2020). As a result, the current evidence supporting short-term HA protocols for procuring beneficial T_c and HRex adaptations (5 – 7 days; based primarily on male data) (Daanen, Racinais & Périard 2018; Guy et al. 2015; Tyler et al. 2016) may not be applicable for female athletes. Practitioners supporting female athletes preparing for thermally challenging events will benefit from a more robust understanding of the minimal effective HA dose to achieve a given response (T_c, HRex, sweat rate).

This study aims to describe the physiological (resting T_c, HRex, sweat rate) and psychophysical [rating of perceived exertion (RPE), thermal sensation, thermal comfort] responses to a short-term (5-day) HA training camp in elite female rugby sevens athletes. Based on previous short-term HA adaptation findings (Daanen, Racinais & Périard 2018; Guy et al. 2015; Tyler et al. 2016), it is hypothesised that resting T_c, HRex, and all perceptual measures will show favourable changes in response to the HA camp, but the 5-day duration will be insufficient for meaningful changes in sweat rate.

METHODS

PARTICIPANTS

Data were collected from a total of 19 female athletes (24.2 ± 4.4 years, 170 ± 4 cm, 71.6 ± 4.9 kg) from a single 2020 Tokyo Olympic Games rugby sevens extended squad based in Sydney, Australia. The athletes commonly train for 10 – 12 hours per week (including 3 – 4 field sessions, 3 – 4 resistance training sessions, and 1 – 2 cross-training or indoor skills sessions) and had been training consistently for 6 months prior to the camp (due to a COVID-19 affected competition season). During this period, accumulated distances on the Yo-Yo Intermittent Recovery Test Level scores were 1509 ± 283 m (estimated VO_2max based on test results: 49.1 ± 2.4 $ml \cdot kg^{-1} \cdot min^{-1}$) (Bangsbo, Iaia & Krustrup 2008).

The full population of professionally contracted international female rugby sevens athletes in the country, available to play at the time of data collection, were recruited. Written informed consent was provided for the project under ethical approval from the University of Technology Sydney (ETH19-4051) Human Research Ethics Committees in the spirit of the Helsinki Declaration.

DESIGN

A descriptive case series study design was conducted in Darwin, Australia during a short-term HA training camp in June 2021 (Australian winter) as part of preparations prior to the Tokyo 2020 Olympic Games (de Korte et al. 2021). During the 5-day data collection period, all athletes took part in normal team training as prescribed by the coaches and strength and conditioning staff (normal training content, as is performed in Sydney, was not altered for this study). Athletes participated in five field-based rugby and conditioning sessions involving a combination of self-paced and constant work rate exercise, four indoor resistance training sessions (air-conditioned facility), and two outdoor cross-training sessions. The cross-training sessions involved a combination of cycle and rower ergometers, bodyweight strength endurance, boxing, and medicine ball exercises. Non-training-related outdoor exposure amounted to multiple hours each day and consisted of group or promotional activities and community functions. Nights were spent in air-conditioned demountable accommodation. Markers of physiological and psychophysical adaptations to HA were collected at various stages during the camp (see Figure 7.1) to describe the time course of responses. The effect of athletes' menstrual cycles was unable to be accounted for, as these are not typically monitored by medical staff. Within the team, athletes choose to manage their menstrual cycle as they see fit.

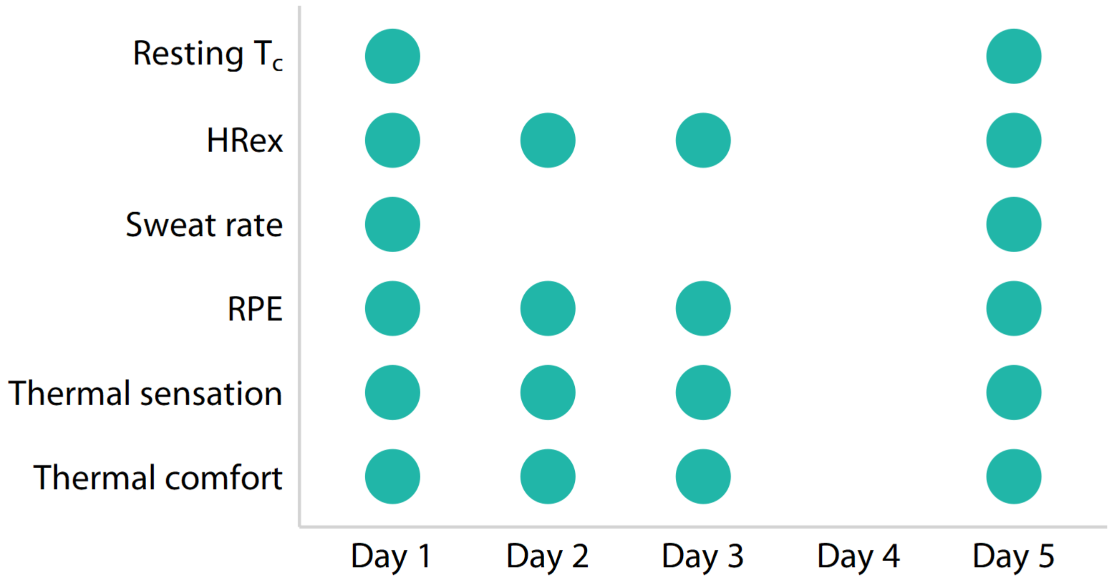


Figure 7.1 Summary of data collection type and frequency from the short-term heat acclimatisation camp. Each dot representing the type of data on the y-axis was collected on the corresponding day on the x-axis. T_c = core temperature; HRex = exercise heart rate; RPE = rating of perceived exertion.

METHODOLOGY

Training during the month prior to the camp was performed at 14.3 ± 2.6°C ambient temperature and 81 ± 15% relative humidity. Weekly total field training loads [measured by Catapult Vector S7 10Hz dual global navigation satellite system / local position system devices (Catapult Sports, Melbourne, Australia)] for the camp and 8 weeks prior are shown in Figure 7.2. The field training load for each session within the camp is summarised in Table 7.1.

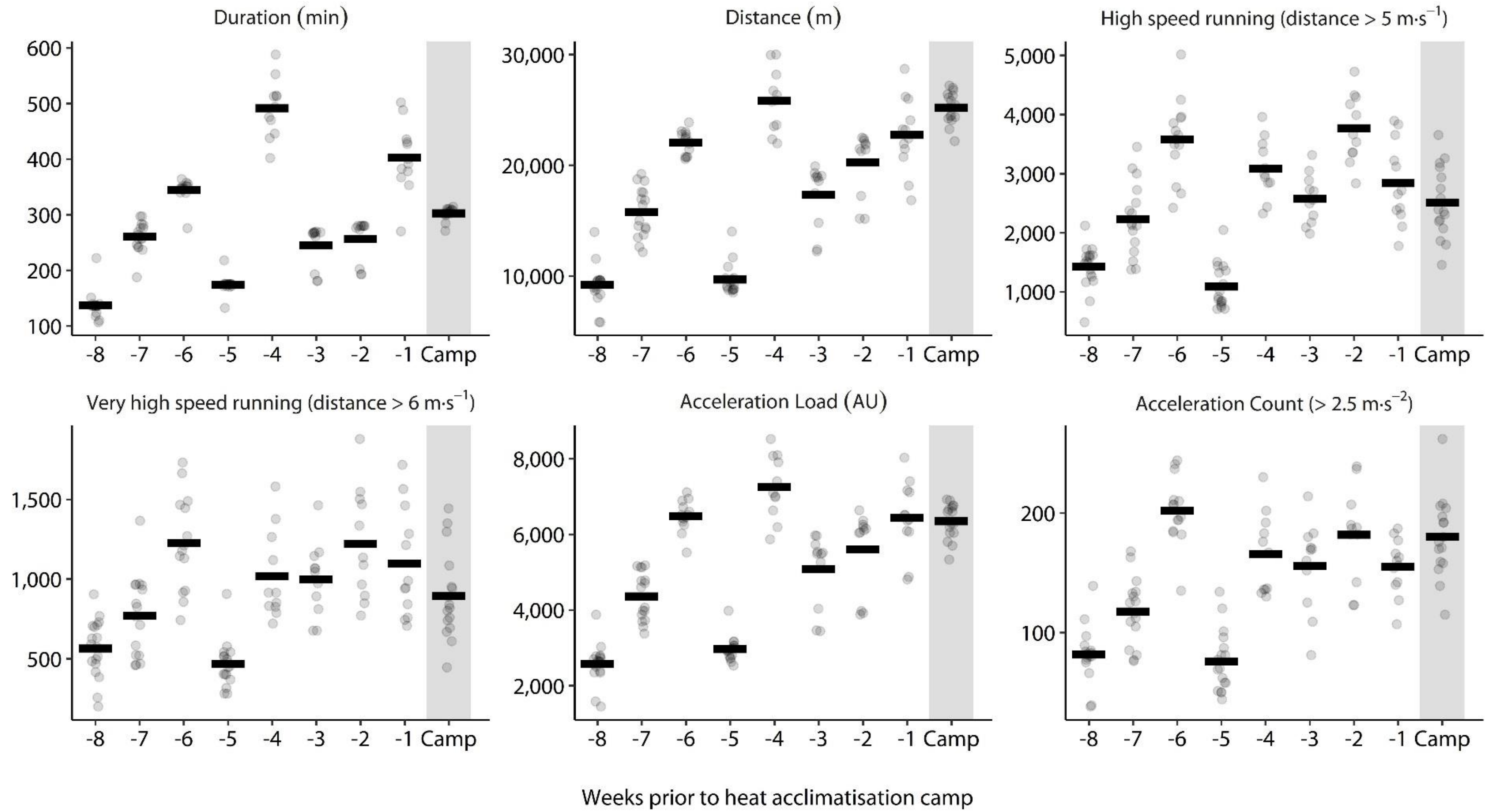


Figure 7.2. Key on-field training volume metrics. Black lines represent the squad average value for each week and grey circles represent individual weekly totals for each squad member. The shaded area indicates data from the training camp in this study. AU = arbitrary units.

Table 7.1 External load for each on-field training session within the camp. Data are presented as mean ± SD.

	Day 1	Day 2		Day 3	Day 4	Day 5
Daily Session	1	1 (AM)	2 (PM)	1	NA	1
Duration (min)	59.4 ± 3.1	52.6 ± 2	64.7 ± 2.6	64.9 ± 3	NA	61 ± 7.6
Distance (m)	4845 ± 309	4943 ± 252	4682 ± 235	5080 ± 422	NA	5669 ± 839
HSR (m > 5 $m \cdot s^{-1}$)	390 ± 110	574 ± 128	387 ± 193	418 ± 167	NA	739 ± 208
VHSR (m > 6 $m \cdot s^{-1}$)	99 ± 48	276 ± 84	108 ± 68	124 ± 55	NA	288 ± 90
Acceleration Load (AU)	1241 ± 102	1223 ± 115	1240 ± 79	1259 ± 154	NA	1387 ± 213
Acceleration Count (> 2.5 $m \cdot s^{-2}$)	34 ± 9	33 ± 8	36 ± 10	37 ± 9	NA	40 ± 12

AU: arbitrary units; HSR: high-speed running; VHSR: very high-speed running

Environmental conditions during the camp were generally hot (see Table 7.2 and Figure 7.3 for full details). Signs and symptoms of exertional heat illnesses (EHI) were collected following the training session using a modified survey instrument (Périard et al. 2017). Specifically, the athletes were asked in a yes/no manner if they had experienced: (i) cramping; (ii) vomiting; (iii) nausea; (iv) severe headache; (v) collapsing/fainting; or (vi) any other symptom that might relate to heat illness (Périard et al. 2017).

Table 7.2 Environmental conditions during outdoor field-based training sessions across the short-term heat acclimatisation camp. All data were collected via a 1 Hz portable weather station (Kestrel 5500, Nielsen-Kellerman Co. USA) during each outdoor training session and presented as mean ± SD.

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**
Temperature (°C)	32.6 ± 1.6	33.0 ± 1.2	33.4 ± 1.3	NA	29.7 ± 1.6
Wet Bulb Temperature (°C)	26.2 ± 1.0	26.1 ± 1.2	27.2 ± 0.9	NA	21.8 ± 0.9
Relative Humidity (%)	61 ± 4	58 ± 4	62 ± 4	NA	50 ± 6
Barometric Pressure (mb)	1011.0 ± 0.3	1011.4 ± 0.4	1011.7 ± 0.3	NA	1013.6 ± 0.1
Wind Speed ($m \cdot s^{-1}$)	0.7 ± 0.5	0.6 ± 0.5	0.6 ± 0.5	NA	0.3 ± 0.5
Dew Point (°C)	24.1 ± 1.0	23.7 ± 1.5	25.2 ± 1.0	NA	18.2 ± 1.2

mb = millibars

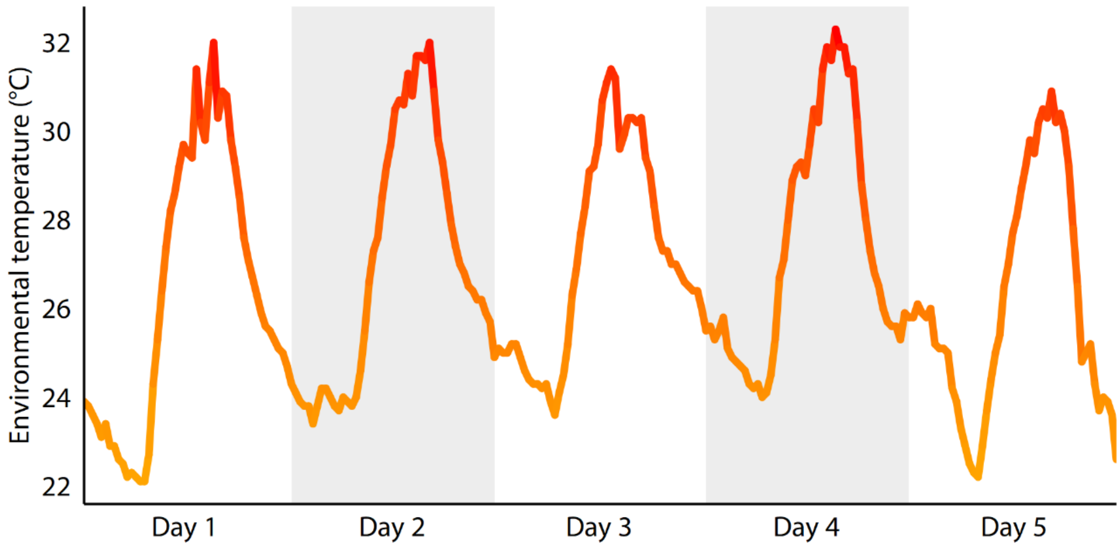


Figure 7.3 Daily variation in environmental temperature across the entire short-term heat acclimatisation camp. Data collected via the Australian Government Bureau of Meteorology website (http://www.bom.gov.au/products/IDD60901/IDD60901.94120.shtml) at 30-minute intervals from a weather station less than 3 km from the team's training base and accommodation.

Athletes ingested an e-Celsius™ telemetric capsule (BodyCap, Caen, France) the night prior to resting T_c data collection. Resting T_c measures were determined by the presence of a stable period of T_c prior to waking whilst lying in bed (occurring around 5:00 – 5:30 am for most). Data were only included within the statistical model when ≥ 5 hours had elapsed post-ingestion, a criterion used previously to ensure the capsule was in the lower intestine (Byrne & Lim 2007; Henderson et al. 2020; Taylor, Thornton, et al. 2019). Resting T_c was sampled at 15 s intervals, with data downloaded at the earliest convenience after waking via a wireless data receiver (e-Viewer, BodyCap, Caen, France). Capsules were prepared, calibrated, and handled as outlined previously (Henderson et al. 2020; Taylor, Thornton, et al. 2019; Travers et al. 2016). The e-Celsius™ system has been determined valid and reliable for intermittent-running exercise (Travers et al. 2016), as well as excellent validity (ICC 1.00), test-retest reliability (ICC 1.00) and inertia in water bath experiments between 36°C and 44°C (Bongers et al. 2018). The e-Celsius™ system has also been used previously within elite rugby sevens matches (Henderson et al. 2020; Taylor, Thornton, et al. 2019) and training (Henderson et al. 2021; Taylor, Stevens, et al. 2019). In the case of technological error or the capsule being passed prior to data collection [this occurred for 6 of the 38 attempted measures (19 participants x 2 measures each)], resting T_c data were not able to be collected.

Cardiovascular fitness changes were indirectly monitored by tracking changes in HRex to a 4-minute submaximal continuous run at 12 km·h^{-1} and recording the mean value of the final 30 s. The submaximal run was conducted as part of the training session's warm-up (see Figure 7.4 for methodology and diagram) (Buchheit, Simpson & Lacome 2020). Data were collected using Polar H1 heart rate monitors (Polar Electro Oy, Kempele, Finland) worn via a chest strap. This approach of monitoring submaximal HRex is common in elite sports (Buchheit, Cholley & Lambert 2016; Thorpe et al. 2016) and is a highly recommended surveillance tool for monitoring positive aerobic-oriented training adaptations (Buchheit et al. 2012). To account for variable environmental temperature between sessions, HRex measures have been adjusted as recommended previously (Lacome, Simpson & Buchheit 2018) to avoid misinterpretation (i.e., noise in HRex from different environmental temperatures being interpreted as fitness changes). This is based upon previous work showing a 1% shift in fractional utilisation (sustainable percentage of VO2max) in response to a 10°C difference in ambient temperature during a 4-minute HRex monitoring run (Lacome, Simpson & Buchheit 2018).

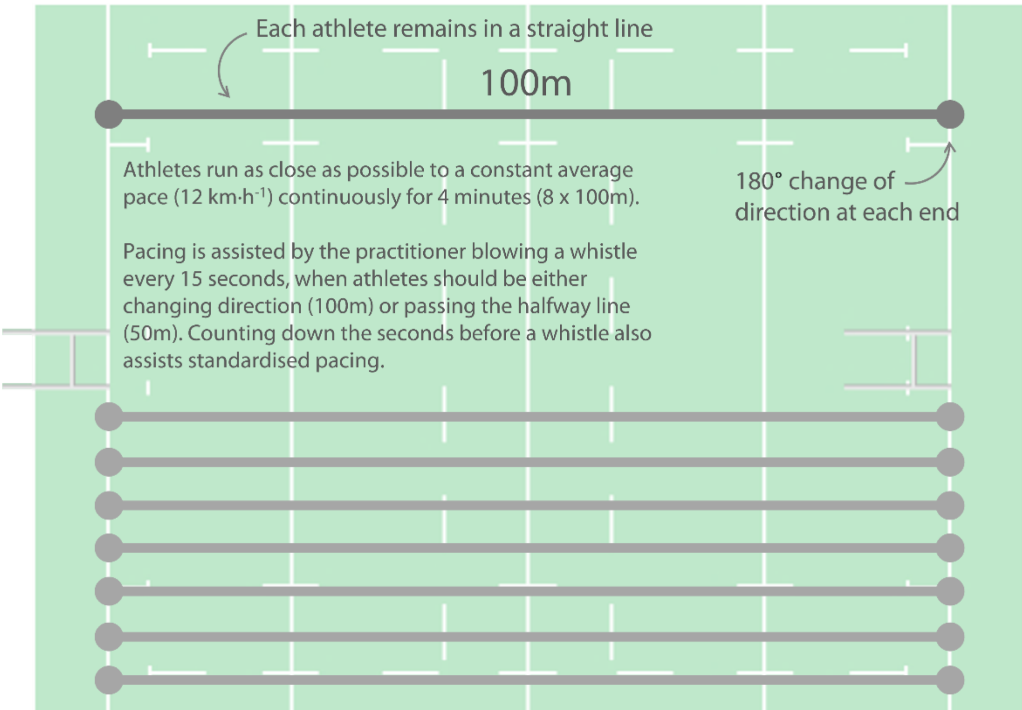


Figure 7.4 Diagram and description of the submaximal standardised 4-minute continuous run method.

Whole-body sweat loss was quantified by determining the change in body mass pre- and post-training (assuming a fluid volume of 1L = 1kg). Athletes were asked to urinate and/or defecate, if necessary, prior to pre-training measurement and not again until post-training measurement. Body mass was measured wearing only underwear, immediately before and after the training session using calibrated scales (BWB-800-S, Tanita, Tokyo, Japan). Each player was provided with an individually named drink bottle that was weighed before and after training to establish the volume consumed during the training session. Body mass loss was corrected for fluid intake but not for respiratory and metabolic water loss/gain. Athletes were instructed to only drink from their own bottles, not spit water out, or pour water on themselves. Drinking behaviour was monitored by the researchers and practitioners to ensure adherence.

Measurements of RPE (CR-10 scale; where 0 = rest and 10 = maximal) (Borg 1982), thermal sensation (17-point category ratio scale; where 0 = 'unbearably cold' and 8 = 'unbearably hot') (Young et al. 1987), and thermal comfort (10-point scale; where 1 = 'comfortable' and 10 = +1 above 'extremely uncomfortable') (Borg 1982) were collected before and immediately following the standardised submaximal run, and upon cessation of the session. All psychophysical data collected from these scales represent how athletes were feeling when asked (i.e., not a session average). In the case of an athlete not completing the standardised submaximal run due to injury or load management concerns, their perceptual data were not collected or used in the analysis of psychophysical responses (this occurred for 4/19 athletes).

All measures were obtained as per Figure 7.1, by the same practitioner using standardised language and procedures.

STATISTICAL ANALYSES

All statistical analyses were performed, and figures were created, using R statistical software (R Core Team 2022). Descriptive statistics are reported as mean ± SD when data is continuous (resting T_c, HRex, sweat rate) or median (IQR) when data is ordinal (RPE, thermal sensation, thermal comfort).

Linear mixed-effects models were fitted on all continuous dependent variables (resting T_c, HRex, sweat rate) using the {lme4} R package (Bates et al. 2015) to determine the effects of the short-term HA camp (with the ordered categorical independent variable of days across the camp). Intercepts were allowed to vary randomly for each athlete, given that some of the variance in the dependent variables is likely associated with the clustering of repeated observations within a single individual. P-values were obtained by Kenward-Roger approximation (Kenward & Roger 1997) which has been shown to produce acceptable Type 1 error rates, even for smaller samples (Luke 2017). Pseudo 'variance explained' (R^2) values were calculated (Nakagawa & Schielzeth 2013) to assess model goodness-of-fit. Approximate partial eta squared effect sizes (η_p^2) were converted from test statistics and degrees of freedom using the {effectsize} R package (Ben-Shachar, Makowski & Lüdecke 2020). Both goodness-of-fit (R^2: 0.02 = *weak*, 0.13 = *moderate*, 0.26 = *substantial*) and effect sizes (η_p^2: *small* = 0.01, *medium* = 0.06, *large* = 0.14) were interpreted using Cohen's recommendations (Cohen 1988).

Ordinal data collected from the psychophysical scales (RPE, thermal sensation, and thermal comfort) were analysed using a Friedman rank sum test to assess change across the HA protocol. Kendall's *W* effect sizes (normalisation of the Friedman statistic) were calculated and assumed values from 0 to 1, indicating no relationship or a perfect relationship, respectively. In the case of a significant Friedman rank sum test, pairwise Wilcoxon signed-rank tests (with Bonferroni correction) were used to identify change between days, and rank-biserial correlations (*r*) effect sizes were calculated to assess the magnitude of change between days. Cohen's recommendations were again used for interpreting both *W* and *r* effect sizes (*small* = $0.1 - 0.3$, *moderate* = $0.3 - 0.5$, *large* > 0.5) (Cohen 1988). All confidence intervals were calculated by using bootstrapping. Using this method, the original data are re-sampled to create many simulated samples from which confidence intervals can be constructed. Perceptual data collected following the standardised submaximal run was used for analysis to determine the effect across the HA camp. Data collected prior to and at the end of training is provided for context and descriptive purposes only, due to variable external loads between sessions making controlled comparisons not possible.

Visual inspection of diagnostic plots did not reveal any obvious deviations from normality or heteroscedasticity. Shapiro-Wilk tests performed on model residuals suggested no evidence of non-normality in all cases except sweat rate, although violations of this assumption within linear models are rarely problematic. The commonly recommended solutions to this problem (e.g., using non-parametric tests, and generalised linear models) have been suggested to represent a greater threat to the reliability of conclusions because of their lower flexibility or robustness (Knief & Forstmeier 2018).

RESULTS

Descriptive data (including athletes with incomplete datasets due to injury, technological error, or the capsule being passed prior to data collection) for all continuous and ordinal outcome measures are presented in Tables 7.3 and 7.4, respectively.

Table 7.3 Descriptive data for all continuous outcome measures. Data presented as mean ± SD (top row) and minimum – maximum (middle row).

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**
Resting T_c (°C)	36.8 ± 0.3 36.3 – 37.2 n = 18	NA	NA	NA	36.8 ± 0.2 36.3 – 37.0 n = 14
HRex (bpm)	175 ± 13 146 – 199 n = 19	170 ± 12 144 – 190 n = 15	170 ± 12 140 – 187 n = 17	NA	171 ± 12 142 – 190 n = 19
Sweat rate ($L \cdot hr^{-1}$)	1.1 ± 0.3 0.8 – 1.8 n = 19	NA	NA	NA	1.0 ± 0.2 0.7 – 1.4 n = 19

T_c = core temperature; HRex = exercise heart rate

Table 7.4 Descriptive data for all ordinal outcome measures. Data presented as median (interquartile range).

		Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**
Pre-session	RPE	NA	NA	NA	NA	NA
	Thermal sensation	4 (3.75 – 4) n = 19	3.25 (3 – 4) n = 16	3.25 (3 – 4) n = 18	NA	3 (3 – 3.5) n = 19
	Thermal comfort	1 (1 – 1) n = 19	1 (1 – 1) n = 16	1 (1 – 1) n = 18	NA	1 (1 – 1) n = 19
Post-standardised run	RPE	3.5 (2.75 – 4) n = 19	3 (2.5 – 3.5) n = 16	4 (3 – 5) n = 17	NA	3 (2.5 – 4) n = 19
	Thermal sensation	5 (5 – 5.5) n = 19	5 (4.375 – 5.5) n = 16	5 (5 – 5.5) n = 17	NA	4.5 (4 – 5) n = 19
	Thermal comfort	3 (2.5 – 3) n = 19	3 (2.375 – 4) n = 16	4 (3 – 5) n = 17	NA	3 (2 – 3) n = 19
Post-session	RPE	5.5 (4.625 – 7) n = 18	6.25 (5 – 7.625) n = 16	7 (6.25 – 7.375) n = 18	NA	5 (4.125 – 6) n = 19
	Thermal sensation	6 (5.125 – 6.5) n = 18	6 (5.5 – 6.5) n = 16	6.5 (6 – 6.875) n = 18	NA	5 (4.25 – 5.75) n = 19
	Thermal comfort	4.5 (3 – 6) n = 18	5 (5 – 6) n = 16	5.5 (5 – 6.5) n = 18	NA	4 (2.5 – 4.5) n = 19

RPE = rating of perceived exertion

Figure 7.5 depicts the effect of the HA camp on each of the physiological outcomes across each day. Table 7.5 summarises the statistical results of the physiological data.

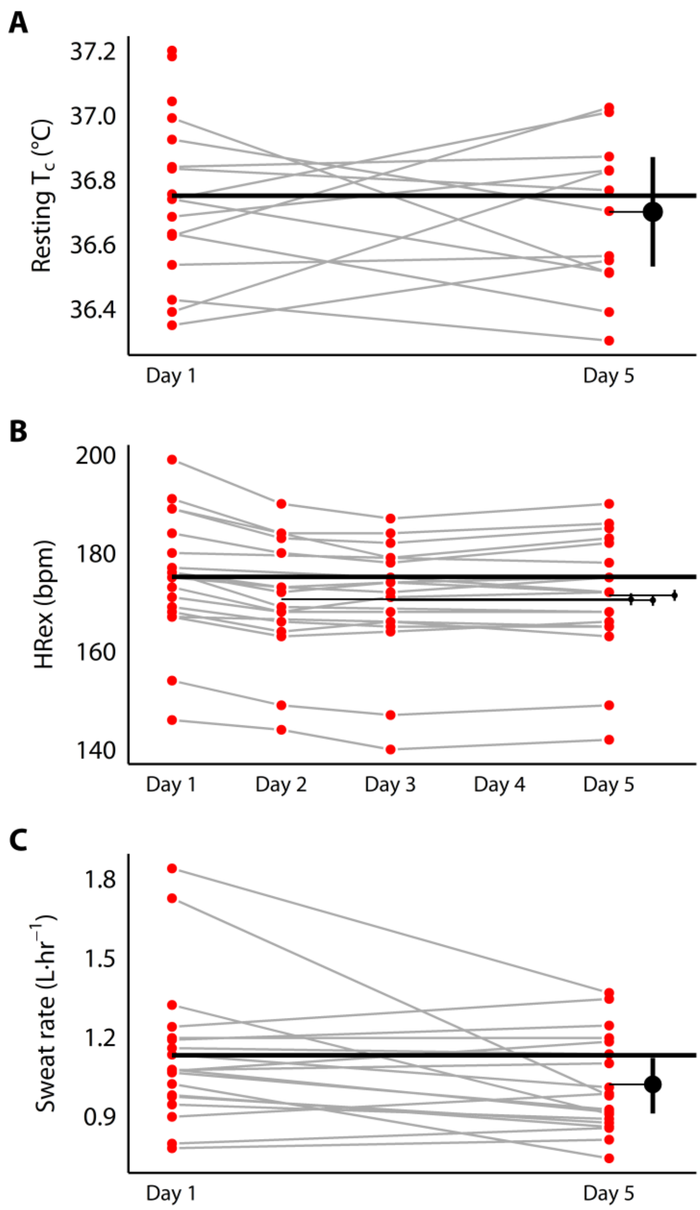


Figure 7.5 Individual data (circles) for each continuous outcome measure (paired observations connected by grey lines). The thick black horizontal line through the entire figure represents the model's intercept (Day 1 estimate). The thinner black lines projecting from each subsequent time point represent the model's estimate at that point. The black dots and vertical error bars to the right represent the model's estimate and associated 95% confidence interval for each timepoint in comparison to the intercept (Day 1). T_c = core body temperature; HRex = exercise heart rate.

Table 7.5 Linear mixed effect model results for all continuous outcome measures.

Resting T_c

Marginal R^2 = 0.01 | Conditional R^2 = 0.27

Parameter	Coefficient (95% CI)	SE	*t*	df error	*p*	η_p^2	Magnitude
Day 1 (Intercept)	36.75 (36.63 – 36.87)	0.06	640.40	27.41	< 0.001		
Day 5	-0.05 (-0.22 – 0.12)	0.08	-0.61	14.71	0.550	0.02 (0.00 – 0.30)	*Small*

HRex

Marginal R^2 = 0.01 | Conditional R^2 = 0.98

Parameter	Coefficient (95% CI)	SE	*t*	df error	*p*	η_p^2	Magnitude
Day 1 (Intercept)	175 (169 – 181)	2.74	63.99	18.55	< 0.001		
Day 2	-5 (-6 – -3)	0.61	-7.50	48.03	< 0.001	0.54 (0.34 – 0.67)	*Large*
Day 3	-5 (-6 – -4)	0.58	-8.16	48.02	< 0.001	0.58 (0.39 – 0.70)	*Large*
Day 5	-4 (-5 – -3)	0.56	-6.71	48.00	< 0.001	0.48 (0.28 – 0.63)	*Large*

Sweat rate

Marginal R^2 = 0.06 | Conditional R^2 = 0.55

Parameter	Coefficient (95% CI)	SE	*t*	df error	*p*	η_p^2	Magnitude
Day 1 (Intercept)	1.13 (1.02 – 1.24)	0.05	21.40	28.29	< 0.001		
Day 5	-0.11 (-0.22 – -0.01)	0.05	-2.20	18.00	0.041	0.21 (0.00 – 0.50)	*Large*

T_c: core body temperature; R^2: coefficient of determination; CI: confidence interval; SE: standard error; df: degrees of freedom; η_p^2: approximate partial eta squared; HRex: exercise heart rate

Resting T_c did not significantly change across the protocol (Figure 7.5A; p = 0.550, η_p^2 = 0.02). Exercise heart rate (Figure 7.5B) showed a large and significant reduction from day 1 to day 5 (175 ± 13 vs 171 ± 12 bpm; p < 0.001; η_p^2 = 0.48). Sweat rate (Figure 7.5C) also showed a significant reduction between day 1 and day 5 (1.1 ± 0.3 vs 1.0 ± 0.2 $L \cdot hr^{-1}$; p = 0.041, η_p^2 = 0.21). The variances explained by individual differences between athletes (random effect coefficient and 95% confidence intervals) were 0.13°C (0.04 – 0.37) for resting T_c, 12 bpm (9 – 16) for HRex, and 0.17 $L \cdot hr^{-1}$ (0.10 – 0.27) for sweat rate.

Figure 7.6 depicts the effect of the HA camp on each of the psychophysical outcomes across each day. Table 7.6 summarises the statistical results of the psychophysical data.

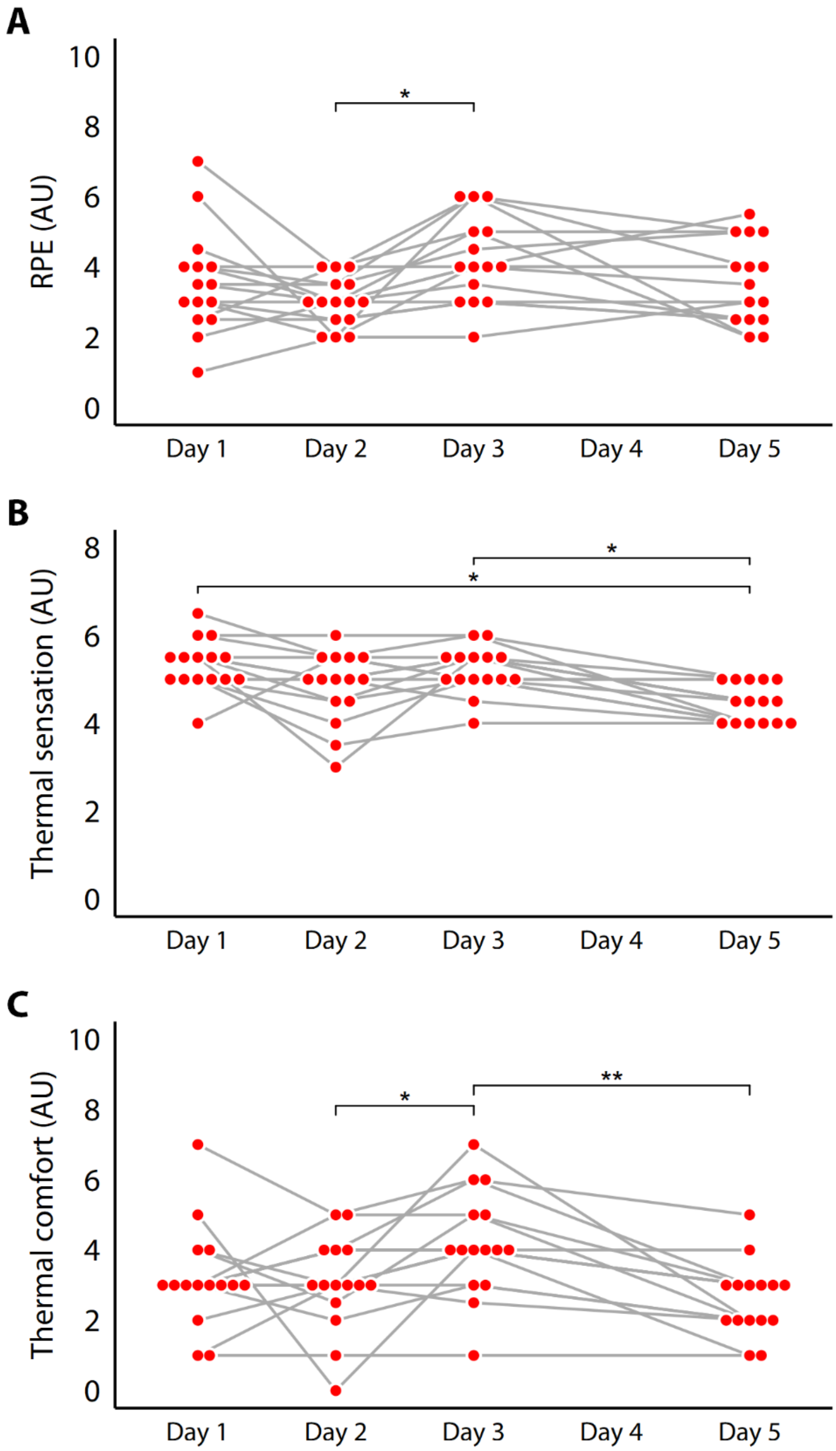


Figure 7.6 Individual data (circles) for each ordinal outcome measure (paired observations connected by grey lines). Statistically significant differences between days signified by * ($p < 0.05$) and ** ($p < 0.01$). RPE = rating of perceived exertion.

Table 7.6 Friedman test and pairwise Wilcoxon signed-rank test results for all ordinal outcome measures.

RPE

Friedman test: χ^2 (3) = 12.8, *p* = 0.005, Kendall's *W* = 0.28 (95% CI: 0.16 – 0.55), n = 15

Reference	Comparison	*W*	*p*	*p.adj*	*r* (95% CI)	Magnitude
Day 1	Day 2	46.5	0.244	1.000	0.35 (0.02 – 0.76)	*Moderate*
Day 1	Day 3	23.5	0.128	0.768	0.43 (0.04 – 0.85)	*Moderate*
Day 1	Day 5	43.5	0.916	1.000	0.04 (0.01 – 0.60)	*Small*
Day 2	Day 3	0.0	0.002	0.002	0.84 (0.76 – 0.89)	*Large*
Day 2	Day 5	16.0	0.075	0.448	0.47 (0.04 – 0.84)	*Moderate*
Day 3	Day 5	49.5	0.152	0.912	0.40 (0.03 – 0.77)	*Moderate*

Thermal sensation

Friedman test: χ^2 (3) = 19.5, *p* < 0.001, Kendall's W = 0.43 (95% CI: 0.21 – 0.71), n = 15

Reference	Comparison	*W*	*p*	*p.adj*	*r* (95% CI)	Magnitude
Day 1	Day 2	46.5	0.057	0.341	0.59 (0.20 – 0.86)	*Large*
Day 1	Day 3	19.0	0.440	1.000	0.15 (0.01 – 0.59)	*Small*
Day 1	Day 5	84.5	0.006	0.039	0.74 (0.45 – 0.89)	*Large*
Day 2	Day 3	13.5	0.078	0.466	0.45 (0.04 – 0.78)	*Moderate*
Day 2	Day 5	45.0	0.078	0.469	0.49 (0.07 – 0.81)	*Moderate*
Day 3	Day 5	66.0	0.003	0.019	0.82 (0.72 – 0.89)	*Large*

Thermal comfort

Friedman test: χ^2 (3) = 16.0, *p* = 0.001, Kendall's W = 0.36 (95% CI: 0.24 - 0.59), n = 15

Reference	Comparison	*W*	*p*	*p.adj*	*r* (95% CI)	Magnitude
Day 1	Day 2	34.0	0.964	1.000	0.02 (0.01 – 0.57)	*Small*
Day 1	Day 3	12.5	0.072	0.433	0.46 (0.06 – 0.80)	*Moderate*
Day 1	Day 5	47.0	0.221	1.000	0.36 (0.03 – 0.80)	*Moderate*
Day 2	Day 3	1.0	0.007	0.043	0.70 (0.39 – 0.86)	*Large*
Day 2	Day 5	50.0	0.131	0.786	0.47 (0.04 – 0.86)	*Moderate*
Day 3	Day 5	91.0	0.001	0.008	0.87 (0.79 – 0.91)	*Large*

RPE: rating of perceived exertion; χ^2: chi-squared; CI: confidence interval; *W:* Wilcoxon test statistic; *p.adj:* adjusted *p*-value after Bonferroni correction for multiple comparisons; *r*: rank-biserial correlation

Thermal sensation (Figure 7.6B) showed a moderate and significant reduction between day 1 and day 5 (median [IQR] = 5 [5 – 5.5] vs 4.5 [4 – 5]; *p.adj* = 0.039; *r* = 0.74). Changes in RPE (Figure 7.6A) were variable between days, and the only significant change was an increase between day 2 and day 3 (3 [2.5 – 3.5] vs 4 [3 – 5]; *p.adj* = 0.002; *r* = 0.84). Changes in thermal comfort (Figure 7.6C) were unclear including a significant increase between day 2 and day 3 (*p.adj* = 0.043; *r* = 0.70) but a significant decrease between day 3 and day 5 (*p.adj* = 0.008; *r* = 0.87).

No EHI symptomology was reported in either group.

DISCUSSION

The present findings show that short-term HA, even as little as 5 days in a hot environment performing moderate-to-high volumes of rugby-specific on-field training, can elicit beneficial changes in HRex (-4 ± 2 bpm; supporting our hypothesis and confirming HRex as a marker of early heat adaptation). Conversely, resting T_c and all perceptual measures did not show consistent changes indicative of favourable adaptation over this timeframe (dismissing our hypothesis), with sweat rate even returning a significant decrease (opposite response to hypothesis). These data will aid in the development of evidence-informed practice for minimal effective HA doses in female team sport athletes, who are underrepresented within the current research.

The positive changes in HRex observed in the present study are consistent with the consensus recommendations on short-term HA effects (Racinais, Alonso, et al. 2015). Despite heterogeneity in study designs and metrics reported in analysed studies, a meta-analysis on the effects of HA found that heart rate-based adaptations are among the first to be observed, and the effect is similar whether short (<7 days) or medium-term (7 – 14 days) HA protocols are performed [long-term HA (>14 days) shown to produce the strongest effect] (Tyler et al. 2016). These findings (based primarily upon male participants) are supported by the present observations in elite female team sport athletes, despite reports that females may require a greater thermal impulse for a given response compared to males (Kirby et al. 2021; Wickham, Wallace & Cheung 2020). Heat-induced reductions in HRex are often attributed to plasma volume expansion (typically occurring after 3 – 4 days) (Senay, Mitchell & Wyndham 1976) allowing increased stroke volume, and therefore maintenance of cardiac output during exercise (Kissling, Akerman & Cotter 2020). Practitioners seeking improvements in cardiovascular stability can confidently use similarly short-duration HA protocols to stimulate such adaptations provided thermal overload is sufficient.

The absence of change in resting T_c contrasts with most of the HA research investigating short-term protocols. Beneficial changes in resting T_c have been observed in response to a 5-day protocol in trained male cyclists [-0.2°C (Neal et al. 2016)], although the validity of this finding may be limited in the context of the present study (elite female team sport athletes). Most T_c adaptations are reported to occur within 7 days of HA, and a recent meta-analysis directly assessing short-term HA protocols showed a moderate effect in reducing resting T_c (-0.17 ± 0.12°C; n = 144) (Tyler et al. 2016). Notably, however, this meta-analysis (including all HA protocol durations) included a total of only 7% (76/1056) female participants (Wickham, Wallace & Cheung 2020). The low sample of female participants likely biases the results and may conceal any sex-dependent effects that may emerge if equivalent samples were available. It has recently been suggested that females require a greater number of HA sessions to stimulate comparable adaptations to males (Kirby et al. 2021; Wickham, Wallace & Cheung 2020), potentially explaining the lack of effect in the present results. Further, much of the data synthesised within the most recent meta-analysis (Tyler et al. 2016) were not from elite or well-trained participants who likely have a partially HA phenotype year-round due to habitually high training loads. Given the changes in $T_{c,}$ a partially HA phenotype evokes, this may potentially confound the effect of these protocols for elite or well-trained populations (Pandolf, Burse & Goldman 1977; Pryor et al. 2019). When pursuing reductions in resting T_c from HA in a lower control but highly ecologically valid training protocol (such as the present study design), practitioners supporting female athletes are advised to opt for longer duration protocols or modify the training content to ensure a greater thermal impulse than the current investigation. Practitioners are also recommended to consider the potential for pre-existing HA (partial or otherwise) when interpreting responses to HA protocols in elite or well-trained populations.

The decrease in sweat rate from Day 1 to Day 5 in the present study is contrary to the expected effect of HA protocols (-0.1 ± 0.2 L·hr^{-1}). Modest elevations in sweat rate are commonly observed in response to short-term HA, and large increases following medium and long-term protocols (Tyler et al. 2016). Increased sweat rate and earlier onset of sweating allow greater evaporative heat loss (primary heat loss pathway during exercise in the heat) and more robust T_c stability (Sawka et al. 2011). A major confounding factor in the present study regarding the sweat rate findings is the difference in environmental conditions between day 1 (32.6 ± 1.6°C, 61 ± 4% relative humidity) and day 5 (29.7 ± 1.6°C, 50 ± 6% relative humidity). Despite this, both these conditions are much more thermally stressful than the typical environmental conditions during training in Sydney for the month prior to the camp (14.3 ± 2.6°C and 81 ± 15% relative humidity). This objective data is supported by athlete's perceptions of the heat between these days with thermal sensation and thermal comfort results being the lowest on Day 5 at all timepoints (pre-session, post-standardised run, and post-session). The expected sweat rate response to short-term HA (modest increase or no conclusive change) is likely obscured by this weather variability, and the observed changes in sweat rate are more likely related to changes in environmental conditions than physiological adaptation. Without greater standardisation of environmental conditions between measures (difficult to achieve in common team sport training environments), it is difficult to draw strong inferences on the dose-response relationship for sweat rate adaptations based upon the present data.

Changes in psychophysical response to heat as a result of short-term HA in the present study were variable, with a combination of positive, negative, significant, and non-significant results. Reductions in thermal sensation were observed [in line with previous reports (Tyler et al. 2016)] on Day 5 but the cooler and less humid environmental conditions on this day prevent an appropriately standardised comparison. Although limited, the available data suggests that HA can reduce perceived levels of effort and thermal perception (Neal et al. 2016) [theorised drivers of volitional behaviour enabling higher self-selected exercise intensities (Flouris & Schlader 2015)]. These findings may be explained by the thermal impulse (duration and/or intensity of heat exposure) in the current study being insufficient for perceptual changes to be realised. The presence of positive and negative results across days in RPE and thermal comfort suggests biological noise is being detected rather than psychophysical adaptation. If tight control of thermal stress is not possible (e.g., outdoor training) and psychophysical adaptation to heat is required, practitioners are advised to prolong HA protocols beyond 5 days or modify training content to ensure the thermal stimulus is sufficient to drive adaptation.

Whilst the present study examined an under-investigated population (i.e., elite female athletes) performing in a field environment during the preparation for a major international sporting event, findings must be interpreted in the context of the limitations. The case series study design, involving no control or comparison group, is prone to selection bias and relatively low on the level of evidence hierarchy. The causality of any responses should therefore not be inferred from this data alone. Beyond being in a location with a consistently hot climate, thermal stress from the outside environmental conditions was uncontrolled and likely modulated observed responses. Perceptual measures used for analysis were collected after only a 4-minute standardised bout of continuous exercise, a short period for psychophysical responses to develop (although the alternative of using post-session measures is confounded by unstandardised external loads during the sessions). Despite these important limitations, this study presents the real-world challenges of both delivering a HA camp and determining its efficacy, without access to specialist equipment and/or being able to perform maximal capacity tests due to periodisation and taper demands/restrictions (even if you could, highly likely weather conditions differ day-to-day).

PRACTICAL APPLICATIONS

- Improved HRex can be obtained and monitored from a 5-day HA protocol simultaneously across a full squad of elite female rugby sevens players (without expensive facilities/equipment or changing training content).
- Substantive changes in resting T_c, sweat rate, and thermal/effort perceptions likely require a greater thermal impulse.

CONCLUSIONS

Beneficial cardiovascular adaptations were obtained and monitored during the 5-day HA protocol simultaneously across a full squad of elite female rugby sevens players (without expensive facilities/equipment or changing training content). However, substantive changes in resting T_c, sweat rate, and thermal/effort perceptions likely require a greater thermal impulse. These data contribute to the development of evidence-informed practice for minimal effective HA doses in female team sport athletes, who are underrepresented in the current research.

CHAPTER 8 | DISCUSSION, RECOMMENDATIONS, AND SUMMARY

MAIN FINDINGS

This thesis demonstrated that elite female rugby sevens players are at risk of hyperthermia during match play and training and that various strategies can be effective in reducing heat load and improving heat tolerance in this population. The strategies discussed require minimal equipment or specialist facilities, are relatively low-cost for most high-performance teams, and can be performed simultaneously on an entire team of rugby sevens athletes. Further, the combined findings provide evidence based on data collected from elite female athletes; an underrepresented population in sport science where small changes in training and preparation can have large implications on performance and associated outcomes (e.g., funding, viewership). The combined findings help narrow the gap between the research evidence and practice through a combination of (1) direct application of the research recommendations to constrained real-world environments, and (2) incorporating clinical expertise and athlete values into the process.

Many of the findings from the studies contained within this thesis were built upon prior findings from research completed in tightly controlled environments with high scientific rigour. Much of the available research evidence in thermal physiology and sports performance was conducted on male endurance athletes (Hutchins et al. 2021; Tyler et al. 2016), upon which many of the popular models of sports thermoregulation used today were developed (Périard, Eijsvogels & Daanen 2021). This disparity is observed across sports science research as a whole with only 34% of participants being female (Cowley et al. 2021). The common and well-supported recommendations and guidelines in place for exercising or competing in the heat (Racinais, Alonso, et al. 2015; Racinais et al. 2023) emerged from this research and our improved understanding of human thermoregulation about stress imposed by sport and exercise. These recommendations include heat acclimation/acclimatisation protocols, hydration strategies, clothing to support ventilation, training in competition-specific conditions, and mixed-method cooling. Although consensus has been reached in many cases as to the efficacy of these methods in mitigating high thermal strain, the findings of the current thesis validate the applicability and test the effectiveness of some of these interventions in a real-world elite rugby setting.

High heat strain is commonly observed in endurance sports, and consistently impairs performance (Nybo, Rasmussen & Sawka 2014). Theories have been developed based on these findings explaining the likely mechanistic causes (altered cardiovascular, cerebral, muscle metabolism, and central nervous system function). Applying these theories to intermittent sports suggests that similar impairments would be observed in these systems under hyperthermic conditions, but this had not been broadly examined beyond individual investigations. The data from studies one and two show, with a high level of evidence in the case of the systematic review (study one), that hyperthermic levels of T_c are also commonly observed across most intermittent sports, including rugby sevens. This has performance implications for intermittent sport athletes as the severe thermal strain has been shown to impair repeated sprint, intermittent sprint, and neuromuscular capacity (Drust et al. 2005; Girard, Brocherie & Bishop 2015; Morrison, Sleivert & Cheung 2004; Nybo & Nielsen 2001; Sunderland & Nevill 2005). Based on the findings from studies one and two, practitioners and coaches supporting intermittent sports athletes are justified to seek interventions aimed at mitigating the high T_c observed in competition. This is consistent with evidence-based practices from endurance sports where interventions aimed at managing T_c are common (Périard et al. 2017).

Current understanding of heat acclimation/acclimatisation research suggests that female athletes require a greater dose (e.g., longer training period, greater heat stress, more sessions) to achieve comparable adaptation to males (Wickham, Wallace & Cheung 2020). Observed differences in sweat response (Gagnon, Crandall & Kenny 2013; Gagnon & Kenny 2011) and aerobic capacity (Yanovich, Ketko & Charkoudian 2020) between sexes have been associated with women experiencing accelerated rates of heat gain. Thermal preparation may also be of greater importance to female athletes due to changes in body temperature, blood pressure, and exercise performance across the menstrual cycle (Charkoudian et al. 2017; Janse et al. 2012). However, the evidence supporting these suggestions are limited because of the low volume of studies including female participants (Hutchins et al. 2021; Tyler et al. 2016). Therefore, evidence-based practice is challenging for practitioners as they are required to rely on their expertise to develop a custom intervention tailored to their athletes' circumstances and preferences.

The present thesis addresses this issue by providing three examples of interventions that observed either (1) a known stimulus for heat adaptation, or (2) evidence of adaptation to heat, from data collected from elite female rugby sevens athletes. Data was not collected from male athletes so comparisons between sexes were not possible, but these findings provide evidence of interventions that have demonstrated efficacy in a highly trained, elite female cohort (who likely maintain a perennial partially-acclimated phenotype as a result of being highly trained). The magnitudes of physiological responses (e.g., heart rate and T_c) from short term heat exposure in this female cohort are consistent with previous findings from primarily male participants (0.17°C reduction in resting T_c and 5 bpm reduction in resting HR (Tyler et al. 2016)). Based on the present observations, practitioners can be confident in developing evidence-based interventions that are likely to result in meaningful improvements in heat tolerance for female athletes. Until an adequate sample of studies are available to provide the necessary statistical power, small differences between sexes in thermoregulation will be difficult to interpret. Currently, in the likely circumstance of no, or only low-quality evidence being available for a given topic on female athletes, practitioners are left to consider the next best available evidence (i.e., adjacent contexts, expert opinion). This requires practitioners to appropriately assess the strength of the findings based on the study design and resemblance of the applied context to their environment.

Whilst there is a substantial volume of research evidence on interventions to mitigate high thermal strain, evidence from practice applied using the expertise of an experienced practitioner and incorporating common feasibility constraints is scarce. The investigations in this thesis were developed through an applied lens. The studies were devised aiming to bridge the gap between the existing research and current practice by providing research application to a high-level rugby sevens setting within the feasibility constraints commonly present in these environments. In pursuit of this aim, the studies within the thesis vary in terms of their level within the hierarchy of scientific evidence (Burke & Peeling 2018). A systematic review (study one) and two controlled trials (studies three and four) contribute a relatively high level of evidence, whilst studies two (cross-sectional) and five (case series) were less controlled and more integrated. Whilst these studies were not as strictly controlled (and therefore have a lower level of evidence than randomised controlled trials), they provide a 'real world' assessment of the theory in practice and incorporate the clinical expertise of the supporting practitioners and modification for unique circumstances of the athletes. This concept is best represented in study five, where a rugby sevens training camp with a national team was performed with a concurrent goal of stimulating heat acclimatisation adaptations. Experienced practitioners planned the training content without modification for the purposes of the study and the training content was rugby sevens-specific in nature. The only real intervention taking place for research purposes is the collection of additional data in an otherwise common training scenario. Incorporating scientific controls within an embedded study design such as this is challenging and often limits the practical assessment of the intervention which was the goal of the study. By contributing both a higher level of evidence research, and lower but embedded research incorporating clinical expertise, athlete values, and feasibility constraints, this thesis seeks to shift the needle closer to evidence-based practice for clinicians working within high-level rugby sevens environments.

The findings of this thesis have impacted the consideration of, and methods used to prepare the Australian national women's rugby sevens team for thermally challenging competition environments. Historically, due to perceived logistical and financial constraints, limited consideration has been given to developing methods for facilitating adaptations that assist thermoregulation and tolerance prior to competing in extreme conditions. The research in this thesis performed within the team has demonstrated that desirable adaptations to heat can be obtained in practice without significant costs or substantially disrupting the rugby training program. This provides benefits for both the athletes and staff as heat-related illness or performance impairment in the athletes is likely to be minimised. This work now promotes proactive planning amongst the high-performance staff at strategic points within the season to increase heat tolerance across the athletes in their care. Currently, the development of plans that include interventions such as those discussed within this thesis are commonly incorporated into the broader training program in the lead-up to specific events.

Collectively, the discussed findings support the development of integrated training plans aimed at maximising physical capacity in rugby sevens through the promotion of heat tolerance adaptations. The availability of specific research evidence collected from rugby sevens environments within this thesis enables practitioners to more confidently devise evidence-based interventions to prevent hyperthermia within the broader rugby sevens training context. Practitioners may consider incorporating methods investigated within this thesis such as acute additional clothing or pre-cooling exposures, or more prolonged acclimatisation regimes into their settings to mitigate the high thermal strain observed in competition. Providing information from ecologically valid studies in this thesis has contributed to a narrowing of the gap from research to practice and provided a meaningful and effective impact on practice with the industry partner. Other practitioners supporting athletes in similar or adjacent contexts may benefit from considering the thermal challenges imposed by their sport and, if necessary, developing evidence-based strategies to minimise harm and maximise performance.

LIMITATIONS

This thesis adopted a combination of observational and experimental approaches to study the effects of thermal interventions on female rugby sevens athletes. There are several limitations arising from the applied nature of the research studies comprising this thesis that need to be acknowledged when interpreting their findings. Firstly, the data collected in studies two to five were all drawn from a single national rugby sevens team. This limits the sample size to the size of the team in match studies (study two) or squad in training studies (studies three to five). Small sample sizes limit the statistical power that is needed to detect meaningful changes and answer research questions. In these circumstances, larger effect sizes are needed to achieve a similar level of conviction that a meaningful effect has occurred. In this case, addressing this limitation will be challenging given the participants involved represent the entire population of full-time professional female rugby sevens athletes in the country. Multi-national studies will be required to answer future research questions more confidently. Further, the presence of data collected from only one team/squad that competes at an elite level means the results obtained may only be directly applicable to this cohort, who share many phenotypic traits due to common environmental exposures.

This thesis builds upon the current theoretical link between high T_c and impaired performance in rugby sevens. The effect of hyperthermia has been repeatedly shown to negatively affect physical and cognitive performance, but at present, research investigating changes in rugby sevens performance markers resulting from changes in thermal strain has not been performed. This is likely due to the complexity surrounding the measurement of performance in rugby sevens where the interplay of technical, tactical, physical, and psychological constructs govern performance. Further, the sample required to detect these changes in rugby sevens performance would be practically unfeasible without many teams over many seasons. The lack of an established link specific to rugby sevens is a limitation of the current thesis, despite the theoretical and mechanistic support for its presence.

Finally, the data collected within the studies of this thesis could all be broadly categorised as representing physical, physiological, or psychophysical constructs of performance. Changes in measures of technical and tactical performance resulting from the interventions were not examined. These constructs have a large influence on performance and are key differentiators of success in sports (Kempton, Sirotic & Coutts 2017; Russell & Kingsley 2011). Future embedded research should incorporate measures of technical and tactical performance into study designs to obtain a more holistic evaluation of the effect of an intervention on sports performance.

PRACTICAL APPLICATIONS

The studies contained in this thesis have provided practical recommendations regarding the preparation of female rugby sevens athletes for thermally challenging competition conditions:

- It is reasonable for practitioners who support rugby sevens athletes (or other intermittent sports athletes) to look for ways to reduce the high heat strain that occurs during competition.
- Wearing additional clothing such as compression garments and a full tracksuit during rugby sevens training can effectively increase T_c and perceived exertion; without negatively impacting external movement or compromising training specificity. Practitioners are advised to carefully consider the timing and frequency of this intervention to maximise athlete tolerance.
- Phase change cooling vests can be worn by athletes before and during a pre-match warm-up in hot conditions to limit the rise in T_c. Shorter periods of wearing the vests (less than 15 minutes before the warm-up) have shown similar benefits but

with reduced time commitment compared to what has previously been performed (data from elite male athletes).

- Elite female rugby sevens players can experience beneficial changes in HRex over a 5-day protocol as a team (without the need for expensive equipment or changes to training content).

- Significant changes in resting T_c, sweat rate, and thermal/exertion perceptions likely require a larger thermal stimulus than what is provided by a short-term (5-day) heat acclimatisation training camp in an uncontrolled but consistently hot climate (average daily high ambient temperature > 30°C and WBGT > 25°C).

THESIS SUMMARY

When athletes compete or train in thermally challenging conditions, they are subject to added physiological strain when compared to the same work in temperate environments. This thesis contains five studies (*Chapters Three to Seven*) that aimed to provide practice-facing solutions to practitioners supporting high-level female rugby sevens athletes. These methods were examined using data collected from elite female athletes; an under-represented population in sport science who are suggested to respond differently to thermal strain than men based on current theories. The first two studies characterised the problem of in-competition hyperthermia across intermittent sports and within elite women's rugby sevens. Studies three and four provided proof of concept for accessible, applied heat acclimatisation and pre-cooling interventions to mitigate thermal strain across a team of elite female rugby sevens athletes. Study five described the responses to a five-day integrated heat acclimatisation program for rugby sevens where training content remained rugby specific. A summary of the findings from the series of investigations conducted as part of the thesis is shown in Table 8.1.

Table 8.1 Summary of the studies conducted as part of this thesis.

Study	Chapter	Title	Participants	Study design	Findings
1	3	Core body temperature in intermittent sports: a systematic review	350	Systematic review	• Almost 90% of the studies including T_c collected during intermittent sports competition found some degree of hyperthermia (T_c >38.5°C), with almost 20% reporting 'marked' hyperthermia (T_c >39.5°C).
2	4	Core temperature changes during an elite female rugby sevens tournament	12	Observational	• Athletes with greater than 6 minutes of involvement in a match often experience Tc associated with reduced intermittent, high-intensity, physical performance (>39°C).
3	5	Additional clothing increases heat load in elite female rugby sevens players	14	Randomised parallel group design	• Training in hot conditions (27.8 – 34.8°C WBGT) provides comparable T_c to matches in temperate conditions (18.5 – 20.1°C WBGT) observed in Study 2. • Additional clothing presents a viable and effective method to increase heat strain.
4	6	Limiting rise in heat-load with an ice-vest during elite female rugby sevens warm-ups	17	Two randomised independent group designs	• Phase change cooling vests worn prior to, and during, the warm-up did limit rise in T_c prior to a match, but only in hot conditions. • Effects in cooler conditions were unclear.
5	7	Responses to a 5-day sport-specific heat acclimatisation camp in elite female rugby sevens athletes	19	Descriptive case series	• Beneficial cardiovascular adaptations were obtained without expensive facilities/equipment or changing training content. • Meaningful changes in resting T_c, sweat rate, and thermal effort/perceptions likely require a greater thermal impulse (e.g., longer camp or higher heat strain).

T_c: core body temperature

The findings of the current thesis contribute to sports thermophysiology knowledge by extending the available evidence to include more female athletes, more intermittent-style sports data, more elite-level participants, and research designs with greater ecological validity. This evidence enables practitioners supporting female rugby sevens athletes (or adjacent sports) to apply interventions more confidently with demonstrated efficacy. Collectively, these findings provide novel support for practitioners in preparing female rugby sevens athletes for hot and humid competition conditions. However, further research is still required to better understand the relationships between high thermal strain and constructs of team sport performance.

DIRECTIONS FOR FUTURE RESEARCH

To expand on the findings of the studies presented in this thesis, it is recommended that further research investigates the following areas:

- The link between hyperthermia and impaired performance in rugby sevens has currently not been examined; only inferred from findings in more controlled environments. This is likely a result of the complexity surrounding the measurement of performance in rugby sevens (and all team sports) whereby the combination of physical, technical, tactical, and psychological constructs contribute to what we collectively term 'performance'.

- Reliable, sensitive, and ecologically valid assessments and tools to determine changes in thermal tolerance, heat acclimation/acclimatisation status, and the effect of cooling interventions. A mixed-methods approach incorporating objective physiological responses and subjective perceptions is likely the most comprehensive strategy when monitoring a training program seeking thermal adaptations.

- Incorporating a more comprehensive and holistic assessment of thermal strain experienced by athletes including measures such as T_{sk} and the gradient of T_c to T_{sk}. The current thesis focused heavily on T_c, but thermal strain is a more complex collective term encompassing multiple interrelated factors.

- Multi-national studies are required to allow research to be conducted within this rare population with much greater statistical power. Currently, the statistical power required to confidently answer research questions in this setting is severely limited by relatively small squad numbers within the current paradigm of intra-team research. World Rugby involvement is likely required to facilitate multi-team research projects that overcome this issue.

- The introduction of technical and tactical measures collected alongside physiological parameters will be key to determining the holistic effects of hyperthermia on performance. These measures are very influential to sporting outcomes, as such, future research should interpret changes within the context of all constructs of performance.

- Improved knowledge of seasonal variation in heat adaptation in athletes, and the subsequent implications on training and preparation for competition, should be considered for future lines of research. This may identify periods of a team's or athlete's annual calendar that have a greater or lesser relative risk of hyperthermia, and therefore greater or lesser relative value in training focused on heat acclimation/acclimatisation.

- Emerging technologies (e.g., thermal energy transfer sensors, sweat composition devices, thermal imaging) may one day enable valid, reliable, and non-invasive measurements informing thermal adaptations with reusable devices. This would enable practitioners and researchers to seamlessly assess athletes — prioritising their needs above our own while effectively applying our skills to gather information that informs training. This could radically change the programming practices of practitioners supporting athletes with heat acclimation/acclimatisation in field settings and enable controlled hyperthermia interventions (i.e., the gold standard of heat adaptation stimulus where a thermal strain is prescribed). This is likely to also enable a substantial improvement in the ease of data collection and volume of research questions able to be answered by practitioners.

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APPENDICES

HUMAN RESEARCH ETHICS COMMITEE OUTCOME AND COMMENTS

HREC outcome and comments – OCTOBER HREC meeting (08/10/19)

Thank you very much for your submission to the UTS HREC. We appreciate the time and effort you have invested in this process.

Please note the comments provided below are generated from an open and collegiate discussion of your proposal by a committee of >20 volunteers (from all walks of life, expertise and background including non-academics and community members). The Committee enjoys reviewing proposals such as yours. However, not all members will be familiar with your research discipline/processes.

To assist our large and diverse Committee to understand your study clearly and to assess the various potential risks, the below comments largely seek clarity and/or additional information from you. We make no assumptions or judgements about your research.

How to respond to the Committee's comments:

1. Provide a detailed response to each comment below
2. Upload this document with your responses on the attachments page
3. Update your application according to the Committee's comments (if applicable) -
   please do not change your application type to 'Amendment to existing approval' - please leave it as the application type you originally requested.
4. Provide any additional documents requested on the attachments page of the application (if applicable)
5. Go to the action tab and click on 'Submit to Ethics Secretariat'

Any changes to documents attached (e.g. participation information sheet, protocol etc.) must be done *in tracked changes.*

Please note: *You have* ***three months*** *to respond to the Committee's comments before your application lapses.*

You will appreciate that the Committee has a duty, obligation and responsibility to ensure that research is undertaken ethically (i.e. safely, honestly, beneficially), for the benefit of participants, communities and researchers, and which is aligned to the:

- Australian Code for the Responsible Conduct of Research (2018)
- Supplementary guidance to support the Code
- National Statement on Ethical Conduct in Human Research (2007)

- Ethical conduct in research with Aboriginal and Torres Strait Islander Peoples and communities: Guidelines for researchers and stakeholders (2018)
- Australian Institute of Aboriginal and Torres Strait Islander Studies Guidelines for Ethical Research in Australian Indigenous Studies (2012)

The Secretariat offers a range of resources and support services to assist researchers in the ethical conduct of research – if you would like more information, we would be pleased to provide this.

Should you have any further queries or concerns, please do not hesitate to contact contact Hannah Foreman, Research Ethics Officer by phone: 9514 2478 or email: Research.Ethics@uts.edu.au

UTS HREC ETH19-4051 – COUTTS (for HENDERSON) – "Maximising rugby sevens performance in hot and humid conditions"

The Committee considered this to be an interesting and well-prepared application. However, the following additional information is requested before approval can be provided:

National Statement 2.2 – General Requirements for Consent

1. The Committee advised that the following information should be provided in the PIS:

   - The PIS should include carbon monoxide rebreathing as a test;
   - The PIS should include how many tests will be performed and what these tests include/involve;
   - The PIS should include under the confidentiality section whether the coach will received identifiable or de-identified group results

   The authors have actioned all the above comments and made the necessary changes to the participant information sheet using track changes.

National Statement 3: Element 2 – Recruitment

2. The researchers are requested to provide additional clarification regarding how an arms-length approach might be applied during the initial stage of recruitment to minimise the risk of coercion;

   To ensure an arms-length approach is taken to recruitment, we consider that an external co-supervisor (Dr. Lee Taylor) would be an appropriate independent third party to deliver information about the project to the potential participants. This third party would address the potential participants and provide a platform *to answer queries or concerns that any potential participants may have with the research.*

National Statement 3: Element 4 – Collection, Use and Management of Data and Information

3. The researchers are requested to provide the full list of variables of what data is being collected or measured;

The full exhaustive list of variables that will be measured is as follows:

Core temperature (Tc)

- Average Tc
- Peak Tc
- Baseline Tc
- Change in Tc from baseline to average & peak

Global Positioning Systems (GPS)

- Duration
- Distance
- High speed running distance (distance covered >5m/s)
- Very high speed running distance (distance covered >6m/s)
- Acceleration load
- Maximal velocity

Perceptual measures

- Rating of perceived exertion
- Thermal comfort
- Thermal sensation

Physiological measures

- Average heart rate
- Maximum heart rate
- Hematocrit
- Haemaglobin
- Plasma volume
- Urine specific gravity(USG)
- Body mass
- Sweat loss
- Sweat rate

Performance / fitness measures

- Change in external work output (measured in watts on a Wattbike cycle ergometer) to a standardised internal load (as measured by heart rate)

4. The researchers are requested to indicate which tests are part of routine training and which tests are new/specific to this study;

   Elements of project data collection routinely performed in normal training:

   - *Physical / technical / tactical training sessions*
   - *All GPS data collection*
   - *USG measurements*
   - *Rating of perceived exertion collection*
   - *Measurement of body mass, sweat loss and rate*
   - *Heart rate data collection*
   - *Active heat acclimation sessions within an environmental chamber*

   Elements of project data collection NOT routinely performed in normal training:

   - *Submaximal fitness testing (Lambert & Lamberts Cycle Test; additional information regarding test in separate document in appendix)*
   - *All core body temperature measurements*
   - *Carbon monoxide rebreathing testing (haematocrit, haemoglobin, plasma volume measures)*
   - *Subjective perceived thermal comfort and sensation measures*

5. The researchers are requested to confirm how blood-tests are being funded for this research project;

   As the necessary skills and technology to perform CO rebreathing blood testing are already present and available to the researchers, only the required consumables (capillary tubes, cleaning solution, mouthpieces, lancets, filters, soda lime) will need to be purchased for the project. The funding for these will be through personal research account of Distinguished Professor Aaron Coutts.

6. The researchers are requested to clarify how data will be collated, and how UTS researchers obtain the data collected.

   Data collection will be conducted by the student researcher and de-identified prior to being saved and managed in the UTS Stash database for collaboration with the other UTS researchers involved in the investigation. As a backup, a local and cloud based file (secured through a password protected computer and cloud account) will be maintained by the student researcher.

The Committee authorised the Executive to approve this application subject to a satisfactory response to the above comments.

RUGBY AUSTRALIA LETTER OF ENDORSEMENT

Australian Rugby Union Limited
Ground Floor, 29 - 57 Christie Street
St Leonards NSW 2065 - Australia
PO Box 115, St Leonards NSW 1590
p: +61 (2) 8005 5555
f: +61 (2) 8005 5699
aru@rugby.com.au
www.rugby.com.au
ABN 36 002 898 544
ACN 002 898 544

To whom it may concern,

Rugby Australia Limited endorse and support the research project, to be conducted in collaboration between University of Technology Sydney and Rugby Australia Limited, entitled "Maximising team sport performance in the heat".

All data collected as part of this project will be provided to the researchers in a de-identified format for analysis.

Rugby Australia Limited understands and agrees that the de-identified findings of this project may be published in peer-reviewed journals and used as part of presentation material at academic and/or industry related conferences.

Kind regards,

Production Note:
Signature removed
prior to publication.

Scott Bowen
Performance Manager 7s Rugby

PARTICIPANT INFORMATION SHEET AND CONSENT FORM

PARTICIPANT INFORMATION SHEET
MAXIMISING TEAM SPORT PERFORMANCE IN THE HEAT

WHO IS DOING THE RESEARCH?

My name is Mitchell Henderson and I am a student at UTS. My supervisor is Prof. Aaron Coutts (aaron.coutts@uts.edu.au)

WHAT IS THIS RESEARCH ABOUT?

Team sport performance in the heat is a lot harder than in a cool temperature, and training in the heat is recommended to improve physical performance in the heat. However, a hot environment is not always available to train in, so this project will experiment with new methods that could potentially help athletes prepare for competition in the heat when a hot environment is not available. This method involves having a hot bath before and after training, and training in additional clothing (i.e. long tights, jumper etc.).

FUNDING

Funding for this project (PhD scholarship for Mitchell Henderson) has been received from Rugby Australia.

WHY HAVE I BEEN ASKED?

We are asking all current members of the Australian Women's rugby sevens squad to participate in this research.

IF I SAY YES, WHAT WILL IT INVOLVE?

All aspects of this research will take place within normal training weeks.

In one training session, you will have a hot bath before and after training (40°C for 30 min) and complete the session in additional clothing (i.e. two pairs of baseliner tights (with shorts on top), long sleeve baseliner t-shirt, short sleeved warm-up jersey, jumper, hat and gloves where possible). You will have control over when you wish to discontinue the bath and remove the additional clothing if you become too hot. These interventions will also be reduced depending/cancelled depending on the temperature of the training session and how hot you get. In the other training session, you will complete the same training, but without the water immersion/additional clothing.

Another session will involve completing a match-day simulation warm up wearing a commercially made athletic cooling vest. You will have control over when you wish to discontinue wearing the vest if you are uncomfortable. These interventions will also be reduced depending/cancelled depending on the temperature of the training session and how cold you get.

For a period of 10-14 days, a applied heat acclimation training block will take place whereby you may be placed in a group that completes either 5-6 exposures of heat acclimation in an environmental chamber performing endurance training (active) or stationary in a hot bath (passive).

Several measures will be taken across the training sessions to determine your thermoregulatory response. These include: 1) core body temperature by a small thermometer (size of a tablet) that you will ingest. These capsules are single use and do not need to be returned to the research team; 2) a urine sample to determine hydration; 3) a finger prick blood sample to determine haematocrit, haemoglobin and plasma volume change; 4) measures of body mass to determine sweat loss; 5) ratings of your feelings of exertion (rating of perceived exertion scale) and temperature (e.g. "how does the temperature of your body feel"). Other measurements will include vertical jump, GPS and heart rate as per normal training.

ARE THERE ANY RISKS/INCONVENIENCE?

The risks associated with this project are low, however, the following risks and risk management strategies have been identified.

1) Core temperature measurement: While the thermometer is inside your body you cannot undergo MRI (as it contains metal) and you are required to wear a 'No MRI' wristband for 24 hours or until you see the thermometer pass.

2) There is a risk of heat illness from the hot-water immersion/training in additional clothing: To prevent heat illness, we have implemented the following risk mitigating procedures; a) constant supervision during all times, b) specific instructions to discontinue the bath if you are feeling too hot, dizzy, lightheaded, or any other usual symptoms; c) Implementation of protocols recommended by previous research. Further, cold-water immersion facilities are available to rapidly cool you if needed and the interventions will be adjusted in hot weather.

3) Risk of infection: To maximise hygiene, the heart rate strap will be thoroughly washed, soaked in disinfectant and washed again as per laboratory standard. All other equipment that contacts the skin will be cleaned with alcohol between participants. The capillary blood samples and urine samples will be collected as per standard laboratory procedures and with single use equipment.

4) The lancet used for the capillary blood sample may cause a light pinch and small bruise on the skin.

DO I HAVE TO SAY YES?

Participation in this study is voluntary. It is completely up to you whether or not you decide to take part.

WHAT WILL HAPPEN IF I SAY NO?

If you decide not to participate, it will not affect your relationship with the researchers or the University of Technology Sydney. If you wish to withdraw from the study once it has started, you can do so at any time without having to give a reason, by contacting Mitchell Henderson (mitchell.j.henderson@student.uts.edu.au).

If you withdraw from the study, any data collected on you outside of normal data collection related to your employment will be destroyed.

CONFIDENTIALITY

Your inclusion in this study will remain confidential. All data you provide during this study will be de-identified before analysis and no identifying information, other than age and gender will be included in reports of the findings. All data will be kept in a locked filing cabinet within in a locked office. Your coach Mitch Henderson would like to use your results to optimise future training and competition practices. If you consent to this, please tick the appropriate box on the consent form.

We would like to store your information for future use in research projects that are an extension of this research project. In all instances your information will be treated confidentially.

The results of this study may be published in a peer-reviewed journal and presented at conferences. No individuals will be identified within these publications. Participants have the option to obtain a summary of the research and a personalised report by contacting the researcher, or by ticking the appropriate box on the consent form. Data and other material gathered from this research will be securely stored at University of Technology Sydney in a locked office and password protected computer. Note that a retention period of 7 years applies to University research material.

WHAT IF I HAVE CONCERNS OR A COMPLAINT?

If you have concerns about the research that you think I or my supervisor can help you with, please feel free to contact me on Mitchell.j.henderson@student.uts.edu.au.

You will be given a copy of this form to keep.

NOTE:

This study has been approved in line with the University of Technology Sydney Human Research Ethics Committee [UTS HREC] guidelines. If you have any concerns or complaints about any aspect of the conduct of this research, please contact the Ethics Secretariat on ph.: +61 2 9514 2478 or email: Research.Ethics@uts.edu.au], and quote the UTS HREC reference number. Any matter raised will be treated confidentially, investigated and you will be informed of the outcome.

CONSENT FORM

MAXIMISING TEAM SPORT PERFORMANCE IN THE HEAT

I ____________________ [participant's name] agree to participate in the research project *Maximising team sport performance in the heat* being conducted by Mitchell Henderson (Mitchell.j.henderson@student.uts.edu.au;). I understand that funding for this research has been provided by Rugby Australia.

I have read the Participant Information Sheet or someone has read it to me in a language that I understand.

I understand the purposes, procedures and risks of the research as described in the Participant Information Sheet.

I have had an opportunity to ask questions and I am satisfied with the answers I have received.

I freely agree to participate in this research project as described and understand that I am free to withdraw at any time without affecting my relationship with the researchers or the University of Technology Sydney.

I understand that I will be given a signed copy of this document to keep.

I agree that the research data gathered from this project may be published in a form that:

☐ Does not identify me in any way

☐ May be used for future research purposes

I am aware that I can contact Mitch Henderson if I have any concerns about the research.

____ ____/____/____

Name and Signature [participant] Date

____ ____/____/____

Name and Signature [researcher or delegate] Date

CHAPTER 3 SEARCH STRING USED ON ALL DATABASES WITH RESULTS

Database	Boolean search string	Limits	Results
Web of Science Core Collection	**TOPIC:** ((athlet* *OR* basebal* *OR* basketbal* *OR* boxer* *OR* cricket* *OR* footbal* *OR* handbal* *OR* hockey* *OR* lacross* *OR* netbal* *OR* player* *OR* polo* *OR* rugb* *OR* soccer* *OR* softbal* *OR* "team* sport*" *OR* tenni* *OR* volleybal*) *AND* ("athlet* perform*" *OR* basebal* *OR* basketbal* *OR* boxing *OR* competit* *OR* cricket* *OR* footbal* *OR* handbal* *OR* hockey* *OR* lacross* *OR* match-play* *OR* "match* play*" *OR* matchplay* *OR* netbal* *OR* polo* *OR* rugb* *OR* soccer* *OR* softbal* *OR* "sport* perform*" *OR* "team* sport*" *OR* tenni* *OR* volleybal*) *AND* ("bod* temperatur*" *OR* "core* temperatur*" *OR* "rectal* temperatur*"))	N/A	621
Ovid MEDLINE	((athlet* or basebal* or basketbal* or boxer* or cricket* or footbal* or handbal* or hockey* or lacross* or netbal* or player* or polo* or rugb* or soccer* or softbal* or "team* sport*" or tenni* or volleybal*) and ("athlet* perform*" or basebal* or basketbal* or boxing or competit* or cricket* or footbal* or handbal* or hockey* or lacross* or match-play* or "match* play*" or matchplay* or netbal* or polo* or rugb* or soccer* or softbal* or "sport* perform*" or "team* sport*" or tenni* or volleybal*) and ("bod* temperatur*" or "core* temperatur*" or "rectal* temperatur*"))	N/A	868
EBSCOhost SPORTDiscus with Full Text	((athlet* OR basebal* OR basketbal* OR boxer* OR cricket* OR footbal* OR handbal* OR hockey* OR lacross* OR netbal* OR player* OR polo* OR rugb* OR soccer* OR softbal* OR "team* sport*" OR tenni* OR volleybal*) AND ("athlet* perform*" OR basebal* OR basketbal* OR boxing OR competit* OR cricket* OR footbal* OR handbal* OR hockey* OR lacross* OR match-play* OR "match* play*" OR matchplay* OR netbal* OR polo* OR rugb* OR soccer* OR softbal* OR "sport* perform*" OR "team* sport*" OR tenni* OR volleybal*) AND ("bod* temperatur*" OR "core* temperatur*" OR "rectal* temperatur*"))	N/A	624