Heat Management Strategies in Elite Rugby Sevens

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Abstract

The purpose of this thesis was to develop and implement heat management strategies for international elite men's and women's rugby sevens teams competing in hot and humid conditions. The first three of six experimental chapters aimed to characterise the physiological, perceptual, and performance perturbations that undertaking rugby sevens specific exercise in hot and humid conditions involves. The following three experimental chapters built upon these characterisations by investigating practical, training-integrated interventions, designed to alleviate the stressors that collectively impair performance.

Study One (Chapter Three) investigated the validity of two practical measures of core and skin temperature (T_c; T_{sk}) during exercise in hot and humid conditions, to identify a measurement tool that could be used during subsequent investigations within the thesis. A tympanic thermometer (to measure tympanic temperature; T_{Tymp}) provided sufficient levels of validity compared to gold-standard gastrointestinal T_c measurement, while a portable infrared thermometer was not valid for measurement of T_{sk}, compared to the criterion measure of hard-wired skin thermistors.

Study Two (Chapter Four) involved the characterisation of T_c, and physiological and performance characteristics that mediate T_c change across a rugby sevens tournament played in hot and humid conditions. Commonly measured variables such as playing minutes, high-speed distance, and total distance significantly predicted post-game T_c during an international rugby sevens tournament played in hot and humid conditions. In turn, post warm-up T_c significantly predicted post-game T_c. Moreover, during each tournament day sequential increases in mean T_c post warm-up were shown, and all post-baseline measures were greater than baseline on day one and day two, indicative of a cumulative increase in T_c across the tournament, particularly during non-competition exercise.

Study Three (Chapter Five) investigated the differences in heat stress between high-intensity running in temperate and hot conditions, while also assessing the application of an off-feet (cycling) heat response test that would be practical to use within the training weeks of an elite rugby sevens team. Acute heat stress resulted in large increases in physiological and perceptual thermal strain when compared to the same exercise stimulus performed in temperate conditions. Furthermore, these increases in thermal strain were associated with a large performance decrement. When comparing running to cycling heat response tests, moderate – large physiological differences were evident, whereas no clear effects on any variables associated with perceptual thermal heat stress were observed. High-intensity running in the heat induces high physiological strain and additional mechanical load that may not be suitable for elite team-sport athletes, meanwhile, high-intensity cycling in the heat induces thermal strain sufficient to drive adaptation and can replicate the perceptual, but not the physiological stress associated with high-intensity running in the heat.

Study Four (Chapter Six) investigated the effectiveness and retention of 10-days of mixed active/passive heat acclimation (HA) integrated within two-weeks of an elite male rugby sevens team training program. Five days of mixed-methods HA elicited some typical physiological, perceptual, and performance adaptations, with an additional five days eliciting further improvements in T_c, sweat rate, and performance during an intermittent sprint heat response test. Furthermore, most adaptations were retained after 16-days of normal training with no additional environmental heat exposure, providing initial evidence for the efficacy of a practical, and ecologically valid, mixed-methods HA protocol within an elite teams training program.

Study Five (Chapter Seven) examined physiological, perceptual and performance changes during and following 10-days of (primarily) passive HA integrated into an elite female rugby sevens teams training program. Meaningful changes in resting and submaximal T_{Tymp}

were achieved only after the full 10-day HA protocol, however these were not well-retained after 15 days without any further heat stimulus. Concurrently, meaningful increases in repeated-sprint peak power output were evident, while no sudomotor or cardiovascular changes were apparent during or post HA. Ten days of (primarily) passive HA elicits minor thermoregulatory and performance benefit when integrated into an elite team's training program. However, such a protocol does not provide a sufficient thermal impulse for adaptations to be retained after 15-days with no further heat stimulus.

Study Six (Chapter Eight) investigated the application of internal and external cooling strategies delivered via the use of ice slurry ingestion and the application of ice towels to the head, neck, and face before and during a repeated high-intensity exercise heat response test within an international elite men's rugby sevens team. The use of this cooling strategy resulted beneficial physiological changes and beneficial changes in indices of thermal perception. Furthermore, there was a small increase in mean time-trial power output during compared to undertaking no cooling.

With very limited previous research on heat management strategies in rugby sevens, particularly in an elite setting, the research within this thesis is among the first to address these critical areas of preparation and performance in an elite rugby sevens context. It is recommended that practitioners include a combination of practical heat acclimation and cooling strategies within their heat management plan when performing in hot conditions.

Table of contents

Abstract 2
Table of contents 5
List of figures 10
List of tables 12
Attestation of authorship 14
Publications and presentations arising from this work 15
Acknowledgements 18
Ethics approval 20
List of common abbreviations 21
Chapter One Introduction and overview of the thesis 22
1.1 Theoretical background 22
1.2 Purpose statement and significance of the thesis 24
1.3 Thesis organisation 25
Chapter Two Heat management strategies: Literature review 26
2.1 Introduction and overview 26
2.2 Physiological mechanisms of adaptation due to heat acclimation 31
2.2.1 Sweating and skin blood flow 31
2.2.2 Blood volume and fluid balance 33
2.2.3 Cardiovascular stability 34
2.2.4 Whole-body and skeletal muscle metabolism 36
2.2.5 Perceptual changes 38
2.2.6 Performance outcomes resulting from heat acclimation 39
2.3 Methods of heat acclimation 41
2.3.1 Self-paced exercise 43
2.3.2 Constant work-rate 43
2.3.3 Controlled hyperthermia 44
2.3.4 Controlled heart-rate exercise 46
2.3.5 Passive HA methods and post-exercise passive HA methods 47
2.4 Length of heat acclimation stimulus 51
2.5 Decay and re-acclimation of heat acclimation 53
2.6 Sex differences in responses to heat stress 56
2.7 Sex differences in responses to heat acclimation 59

2.8 Applied considerations for heat acclimation in an elite team sport context 63
2.8.1 Heat response or heat stress testing 65
2.9 Measurement of body temperature variables 67
2.10 Cooling strategies 72
2.10.1 Pre-cooling 75
2.10.2 Per-cooling 77
2.11 Literature review summary 79
2.12 Research questions 81
Chapter Three Validity of a tympanic thermometer and thermal imaging camera for measuring core and skin temperature during exercise in the heat 83
Prelude 83
3.1 Abstract 84
3.2 Introduction 85
3.3 Materials and methods 88
3.3.1 Participants 88
3.3.2 Study design 88
3.3.3 Core temperature (T_c) 88
3.3.4 Skin temperature (T_{sk}) 89
3.3.5 Statistical analysis 90
3.4 Results 92
3.5 Discussion 97
3.6 Conclusion 100
Chapter Four The relationship between physiological and performance variables during a hot/humid international rugby sevens tournament 101
Prelude 101
4.1 Abstract 102
4.2 Introduction 103
4.3 Methods 105
4.3.1 Core temperature (T_c) 105
4.3.2 Sweat rate and sweat electrolytes 106
4.3.3 Cooling strategies 107
4.3.4 Environmental conditions 107
4.3.5 External load 107
4.4 Statistical analysis 108

4.5 Results 109
4.6 Discussion 115
4.7 Practical implications 118
4.8 Conclusion 119
Chapter Five Evaluation of an off-feet heat response test for elite rugby sevens athletes . 120
Prelude 120
5.1 Abstract 121
5.2 Introduction 122
5.3 Materials and methods 124
5.3.1 Subjects 124
5.3.2 Experimental design 124
5.3.3 RUN Heat response tests 125
5.3.4 CYCLE:HOT Heat response test 125
5.3.5 Physiological measurements 126
5.3.6 Perceptual measurements 127
5.3.7 Statistical analysis 127
5.4 Results 129
5.5 Discussion 132
5.6 Practical applications 134
5.7 Conclusion 134
Chapter Six Practical application of a mixed active and passive heat acclimation protocol in elite male rugby sevens athletes 135
Prelude 135
6.1 Abstract 136
6.2 Introduction 137
6.3 Methods 140
6.3.1 Participants 140
6.3.2 Design 140
6.3.3 Heat response test 141
6.3.4 Active HA sessions 141
6.3.5 Hot water immersion (HWI) sessions 143
6.3.6 Physiological measurements 144
6.3.7 Perceptual Measurements 144

6.4 Statistical analysis 145
6.5 Results 146
6.5.1 Physiological measurements 146
6.5.2 Perceptual measurements 148
6.5.3 Performance measurements 148
6.6 Discussion 153
6.7 Practical applications 157
6.8 Conclusion 158
Chapter Seven Heating up to keep cool: Benefits and persistence of a practical heat acclimation in an elite female rugby sevens team 159
Prelude 159
7.1 Abstract 160
7.2 Introduction 161
7.3 Methods 164
7.3.1 Subjects 164
7.3.2 Design 164
7.3.3 Heat response test 165
7.3.4 Post-exercise sauna sessions 166
7.3.5 Hot water immersion (HWI) sessions 167
7.3.6 Physiological measurements 167
7.3.7 Perceptual measurements 168
7.4 Statistical analysis 168
7.5 Results 169
7.5.1 Physiological measurements 172
7.5.2 Perceptual measurements 172
7.5.3 Performance measurements 172
7.5.4 Heat acclimation sessions 173
7.6 Discussion 176
7.6.1 Perspectives and considerations 178
7.7 Conclusion 179
Chapter Eight Small performance effects of a practical cooling strategy in elite team sport athletes 180
Prelude 180
8.1 Abstract 181

8.2 Introduction 182
8.3 Methods 185
8.3.1 Subjects 185
8.3.2 Design 185
8.3.3 Heat response test 186
8.3.4 Physiological measurements 187
8.3.5 Perceptual measurements 188
8.4 Statistical analysis 188
8.5 Results 189
8.6 Discussion 192
8.7 Practical applications and considerations 194
8.8 Conclusion 195
Chapter Nine General discussion 196
9.1 Thesis aims 196
9.2 Summary of findings 197
9.2.1 Characterisation studies 197
9.2.2 Intervention studies 202
9.3 Practical applications 211
9.4 Limitations 214
9.5 Future directions 217
References 220
Chapter Ten Appendices 252
Appendix One Presented abstracts 252
Appendix Two Co-authorship forms 256
Appendix Three Ethical approvals 262

List of figures

Figure 2-1: Graphic overview of the common methods, modes, activity, conditions, and durations used for heat acclimation among previous literature.. 42

Figure 3-1: Bland–Altman plot indicating the mean bias (solid line) and 95% limits of agreement (dotted lines) in temperature between the ingestible telemetry pill (T_c) minus a tympanic thermometer $T_{c(Tymp)}$ before, during, and after exercise in hot (30 °C) and humid (60% relative humidity) conditions. 95

Figure 3-2: Bland–Altman plot indicating the mean bias (solid line) and 95% limits of agreement (dotted lines) in temperature hardwired skin thermistors (Tsk) minus a handheld thermal imaging camera (Tsk(IR)) before, during, and after exercise in hot (30 °C) and humid (60% relative humidity) conditions. 96

Figure 4-1: Individual core temperature (T_c: °C) across pre-defined measurement periods during day one (panel A) and day two (panel B) for one international team during the Oceania rugby sevens tournament. 113

Figure 4-2: Change in individual core temperature (ΔT_c: °C) across pre-defined measurement periods during day one (panel A) and day two (panel B) for one international team during the Oceania rugby sevens tournament. 114

Figure 5-1: Schematic of the Heat Response Test (HRT) protocols. 127

Figure 5-2: Mean (± 90% CL) Tympanic Temperature (°C) at each measured timepoint for the three interventions. 129

Figure 5-3: A-B: Changes (mean ± CL) in thermoregulatory markers including Tympanic temperature (T_{Tymp}), Heart Rate (HR), Thermal Sensation (TS), Thermal discomfort (TDC), Rate of Perceived Exertion (RPE), Thirst, Sweat Rate and Performance during different heat response testing protocols.. 131

Figure 6-1: Overview of the mixed-methods heat acclimation timeline, including weekly mins of heat exposure. 141

Figure 6-2: Resting (Figure 2a), Submaximal exercise (Figure 2b) and End exercise (Figure 2c) rectal temperature (°C) during Heat Response.. 147

Figure 6-3: Mean (± 95% confidence limits) Power Output (W; closed circles) and Fatigue Index (%; closed squares) during Heat Response Tests Pre-HA, Mid-HA (5 days), Post-HA (10 days) and Decay (+16 days).. 149

Figure 7-1: Overview of the heat acclimation timeline. 165

Figure 7-2: Resting (Figure 2a), Submaximal exercise (Figure 2b) and End exercise (Figure 2c) tympanic temperature (°C) during Heat Stress Tests Pre-HA, Mid-HA (three-days), Post-HA (nine days) and Decay (+15 days after Post-HA).. 174

Figure 7-3: Mean (± 95% confidence limits) Power Output (W; closed circles) and Fatigue Index (%; closed squares) during Heat Stress Tests Pre-HA, Mid-HA (5 days), Post-HA (10 days) and Decay (+15 days).. 175

Figure 8-1: Schematic of the HOT and COOLING conditions 186

Figure 8-2: Mean (± SD) tympanic temperature (°C) at each measured timepoint for the two interventions.. 191

List of tables

Table 2-1: Heat acclimation adaptations and outcomes that support exercise performance in the heat. 28

Table 2-2: Cardiovascular adaptations associated with heat acclimation that led to improved cardiovascular stability 36

Table 2-3: Sex differences in the factors influencing the thermal load accrued during HA sessions. 62

Table 2-4: Overview of different cooling techniques used for pre-, per-, and post-cooling. .. 74

Table 3-1: Thermometer Specifications 91

Table 3-2: Mean ± SD values for core temperature (T_c) between a core temperature pill ($T_{c(Pill)}$) and tympanic thermometer ($T_{c(Tymp)}$) at rest, exercise, and recovery. 93

Table 3-3: Weighted mean (± SD) values for skin temperature (T_{sk}) between the hard-wired skin thermistors ($T_{sk(T)}$) and the infrared camera ($T_{sk(IR)}$) at $_{)}$) at rest and exercise. 94

Table 4-1: Local time, environmental conditions, playing minutes, running distance (m), game high speed distance (m), and pre- post game body mass loss (kg) for one international team during all games (1-5) at the Oceania men's rugby sevens tournament. 110

Table 4-2: Results of linear mixed-effects analysis assessing the effect of playing minutes, game high speed distance (m), running distance (m), post warm up core temperature (T_c; °C), and body mass loss (kg) on individual post-game T_c across all games for one international team during the 2018 Oceania men's rugby sevens tournament. 111

Table 4-3: Results of linear mixed-effects analysis assessing the effect of playing minutes, game high speed distance (m), running distance (m), post warm up core temperature (T_c; °C), and body mass loss (kg) on individual post-game T_c across all games for one international team during the 2018 Oceania men's rugby sevens tournament. Only data for athletes that played > 6 min in any game is included. 112

Table 5-1: Grouped mean (± SD) and mean differences [mean difference ± 90% confidence limits (Cohens d)] for all variables for RUN:AMB, RUN:HOT and CYCLE:HOT Heat Response Tests. 130

Table 6-1: Mean ± SD for variables during heat response tests (HRT) pre-, mid-, post-, heat acclimation (HA) and +16 days (decay). 150

Table 6-2: Mean difference ± 90% confidence limits; (Cohen's *d*) for variables during heat response tests (HRT) pre-, mid-, post-, heat acclimation (HA) and +16 days (decay). 151

Table 6-3: Mean ± SD power output (W) and thermoregulatory variables during exercise (active) and passive hot-water immersion (HWI) heat acclimation sessions on week one and week two. 152

Table 7-1: Participant characteristics and contraceptive type use.. 164

Table 7-2: Mean ± SD for variables during heat response tests (HST) pre-, mid-, post-, heat acclimation (HA) and +15 days (decay). 170

Table 7-3: Mean difference ± 90% confidence limits; (Cohen's *d*) for variables during heat response tests (HST) pre-, mid-, post-, heat acclimation and +15 days (decay)................... 171

Table 7-4: Mean ± SD self-reported exposure time, temperature, thermal sensation, and thermal comfort during self-directed passive hot-water immersion (HWI) heat acclimation sessions across the HA protocol... 173

Table 8-1: Grouped mean (± SD) and mean differences [MD ± 95% CL (Cohens d)] for all variables for HOT and COOLING Heat Response Tests. 190

Attestation of authorship

"I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of university or institution of higher learning."

Stephen Fenemor

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Publications and presentations arising from this work

Publications

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Fenemor, S. P., Driller, M. W., Gill, N., Mills, B., Casadio, J., & Beaven, C. M. (2022). Practical application of a mixed active and passive heat acclimation protocol in elite male Olympic team sport athletes. *Applied physiology, nutrition, and metabolism*. Advance online publication. https://doi.org/10.1139/apnm-2022-0112

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Fenemor, S. P., Gill, N. D., Driller, M. W., Mills, B., Casadio, J. R., & Beaven, C. M. (2022). Evaluation of standard cooling practises in elite rugby sevens athletes. *Research Quarterly for Exercise and Sport*. In review

Presentations

Fenemor, S. P., Gill, N. D., Driller, M. (2018). Heat Response Testing in Elite Rugby Sevens Athletes; An Eye to Tokyo 2020. Presented at Sport and Exercise Science New Zealand Conference, Dunedin, New Zealand.

Fenemor, S. P., Gill, N. D., Mills, B., Driller, M. & Beaven, C. M. (2019). Characterisation of core temperature response to an international rugby sevens tournament played in hot and humid conditions. Presented at Sport and Exercise Science New Zealand Conference, Palmerston North, New Zealand.

Fenemor, S. P., Walsh, K., Davie, C., Wharemate, J., van der Laan, M., Carson, D., Olsen, J., & Beaven, C. M. (2019). Beat the heat: The effectiveness of a practical, cold water arm immersion protocol during a simulated rugby sevens protocol. Presented at Sport and Exercise Science New Zealand Conference, Palmerston North, New Zealand.

Fenemor, S. P., & Beaven, C. M. (2020). Cold-water immersion of the arms as a cooling strategy during repeated sprint exercise. Presented at Sport and Exercise Science New Zealand Conference, Christchurch, New Zealand.

National/International Invited Speaking

Fenemor, S. P., Anderson, B,. McNeil, C,. Smith, B,. Herbert-Losier, K,. & Beaven, C. M. (2021). Kaupapa Kōrero Tauranga: The Tokyo Experience - a round table discussion with Q & A. University of Waikato, Tauranga

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Ethics approval

Ethical approval for all research within this thesis was obtained through the University of Waikato Faculty of Heath Ethics Committee (HREC(Health)). See Appendix Four for approval letters. Each study and corresponding HREC(Health) Ethics Approval Number is outlined below:

• Chapter 3: Ethics approval number 2016#9

• Chapter 4-8: Ethics approval number 2018#64

List of common abbreviations

ANOVA	Analysis of variance
AU	Arbitrary unit
°C	Degrees Celsius
FATIGUE%	Fatigue index percentage
HA	Heat acclimation
HR	Heart rate
HRT	Heat response test
HWI	Hot water immersion
MPO	Mean power output
PPO	Peak power output
RH	Relative humidity
RPE	Rating of perceived exertion
R-SPRINT	Repeated intermittent sprint
SWC	Smallest worthwhile change
T_c	Core temperature
T_{Tymp}	Tympanic temperature
T_{Skin}	Skin temperature

Chapter One Introduction and overview of the thesis

1.1 Theoretical background

Human core body temperature is regulated within a narrow range, typically between 36.5 and 37.5 °C (Tansey & Johnson, 2015). During exercise, increased metabolic activity liberates heat from the exercising muscles, which is then dissipated to maintain a steady thermal state. While this steady thermal state is generally maintained, exercise in a hot and/or humid environment imposes a major stress on the human body's ability to preserve physiological stability, due to a decrease in the thermal and water vapour pressure gradients between the body and the environment, thus impairing heat exchange (Cheung et al., 2000). Briefly, the mechanisms of heat exchange from the body to the environment can be via dry (radiant, conductive, convective) or wet (evaporative) pathways. In humans, dry heat exchange is dependent on the temperature gradient from the core to periphery, and subsequently from the periphery to the environment. Primarily, the potential for evaporative heat loss is determined by the water vapour pressure gradient between the skin surface and the environment. This evaporative potential can be modified by physiological adaptations, environmental conditions, and clothing. A compensable environment occurs when all of these factors result in no net heat storage in the body, while an uncompensable environment results in heat being stored in the body and thus contributes to increased physiological strain, particularly when combined with exercise (Cheung et al., 2000; Galloway & Maughan, 1997).

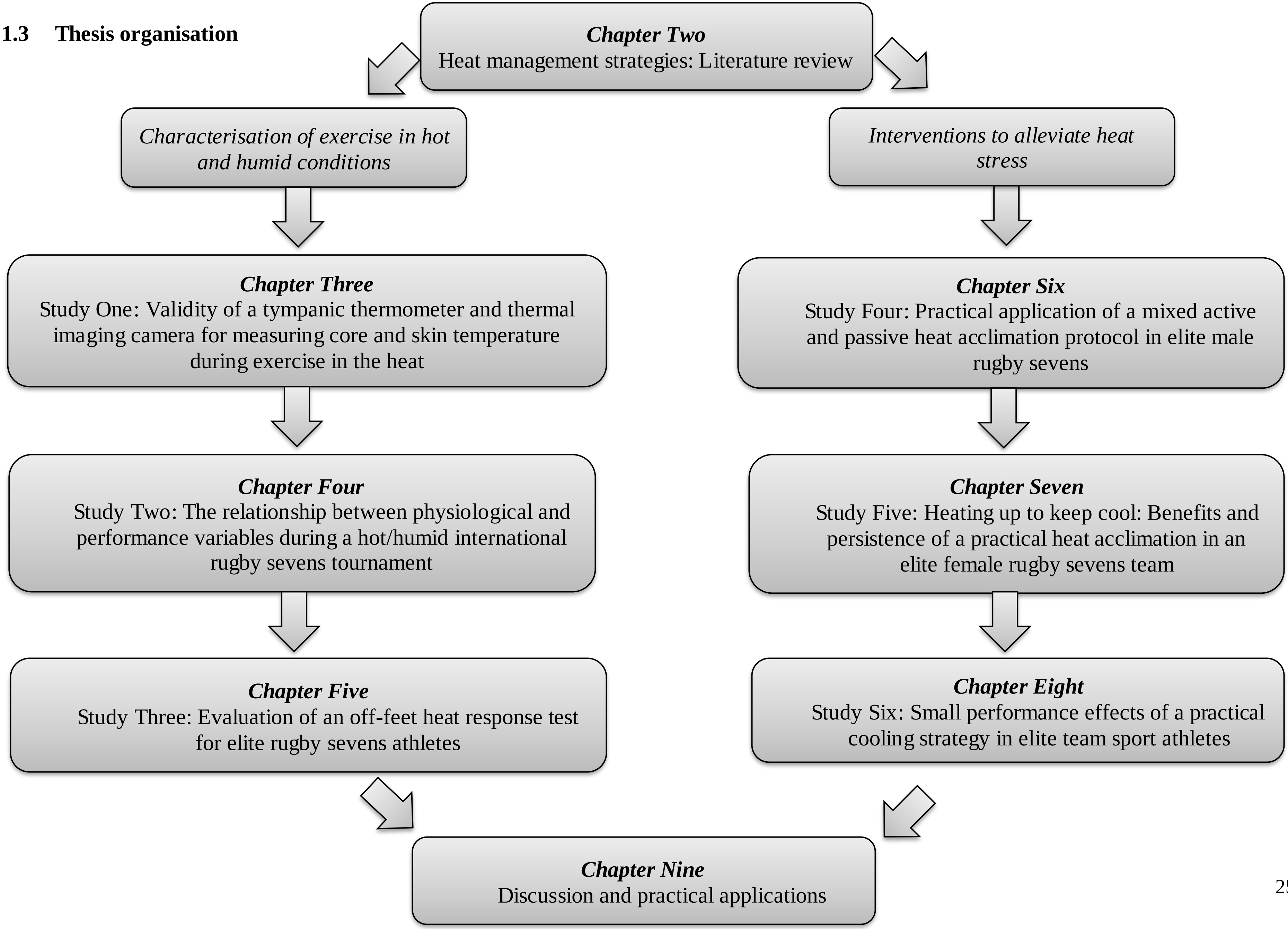
Human adaptation to environmental heat stress has been well reviewed among scientific literature. Some of the first observations included the observation of adverse effects arising from the high temperature and humidity in deep mines (Dreosti, 1935); with early suggestions that occupational heat acclimatisation could be moved to laboratory-based assessments of individual heat tolerance, followed by a period of heat acclimation *before* workers were sent to the deep mine (Dreosti, 1935). As such, early heat acclimation studies investigated applications in workplace (Lind & Bass, 1963; Strydom et al., 1966; Wyndham et al., 1968; Wyndham & Strydom, 1969), and military contexts (Fox et al., 1963; Pandolf et al., 1977). Overall, these studies made the clear indication that an increased work rate at the same relative intensity was possible following periods of heat acclimation. While the mechanisms and time course of adaptation, along with general benefits to occupational and athletic performance were discussed throughout this time (Nadel et al., 1974a; Pandolf et al., 1977; Shapiro et al., 1980; Shvartz et al., 1977) the majority of the research was based on low- to moderately-trained individuals, exercising at low intensities, across many days, which has only limited applicability to an athletic context (Armstrong & Maresh, 1991)

While the adaptations to heat stress in occupational contexts were well-regarded, Galloway and Maughan (1997) demonstrated a clear effect of ambient temperature on the capacity to perform prolonged exercise. Subsequently, research progressed into how adaptations to heat stress can be applied within human performance contexts. In endurance sports, it was demonstrated that heat acclimation can improve markers of endurance performance (Patterson et al., 2004b; Taylor & Cotter, 2006) and endurance performance itself [e.g. 60-min time trial performance (Lorenzo et al., 2010)]. While the mechanisms and applications of heat acclimation strategies are becoming well-understood, some factors, such as the application of heat acclimation strategies to intermittent exercise / team sports and the sex differences in human thermoregulation and adaptation have been largely ignored, and are still not fully elucidated (Gibson et al., 2019a; Yanovich et al., 2020).

1.2 Purpose statement and significance of the thesis

With World Rugby Sevens Series tournaments, and pinnacle rugby sevens events (e.g., Olympic Games, World Cups, Commonwealth Games) often being played in hot and/or humid environmental conditions, the inclusion of appropriate heat management strategies when preparing for such tournaments are well-indicated. Consideration of the multiple factors influencing heat acclimation induction and retention, along with practical considerations for integration within an elite training schedule, creates complex questions regarding the optimal design of heat acclimation protocols. Furthermore, similar practical and logistical considerations can impact upon cooling strategies use in such a context. As a result, the purpose of the current research was to develop and implement best-practise heat management strategies within elite men's and women's rugby sevens teams. The underlying objective was to ensure that the New Zealand national rugby sevens teams were adequately prepared for the un-paralleled environmental conditions at the Tokyo 2020 Olympic Games. While the research was designed to be specific to a rugby sevens team, the application of the current findings are also applicable to other team / invasion sports that involve repeated high intensity efforts. With very limited previous research on heat management strategies in rugby sevens, particularly in an elite setting, the research within this thesis is among the first to address these critical areas of rugby sevens preparation and performance in an elite setting.

1.3 Thesis organisation



Chapter Two Heat management strategies: Literature review

2.1 Introduction and overview

The physiological strain associated with undertaking exercise in hot environmental conditions far exceeds that of exercise of the same intensity in cool conditions (Taylor & Cotter, 2006). Acutely, this increase in physiological strain causes increases in core body temperature, which have been associated with exercise performance decreases in a variety of contexts, including endurance, short-duration (Racinais et al., 2015; Taylor & Cotter, 2006), and some team/intermittent sports (Sunderland et al., 2008). In turn, the development of hyperthermia has been directly linked to neuromuscular, cardiovascular, metabolic, and perceptual alterations that facilitate fatigue (Cheung & Sleivert, 2004). As a result of the deleterious effects of acute exercise in the heat, the focus of much of the resulting research concerns how best to alleviate the physiological strain caused by exercise in hot environmental conditions (Tyler, Reeve, Hodges, & Cheung, 2016; Tyler, Sunderland, & Cheung, 2015). Broadly, these can be grouped into three main interventions that can alleviate physiological strain resulting from heat stress; physiological adaptation to heat, cooling interventions prior to (i.e., pre-cooling) and during (i.e. per-cooling) exercise, and fluid replacement.

By nature, the mechanism of human adaptation is to expose the body to repeated periods of physiological strain so that morphological, chemical, functional and physiological changes can occur (Taylor, 2014). Subsequently, these changes act to reduce physiological strain during later exposures to that stressor. In the case of heat stress, human adaptation requires a series of increases in body temperature (often referred to as thermal impulses). If these thermal impulses exceed an individual's threshold for adaptation, then these impulses will facilitate growth within the physiological reserve range. If these impulses are insufficient, adaptation will either not occur, or be sub-optimal (Taylor, 2014). As such, heat adaptation involves the repeated exposure to sufficiently hot conditions, either using artificial heat sources, such as an environmental chamber, heated room, spa or sauna (i.e. heat acclimation), or a suitable outdoor environment (i.e. heat acclimatisation) (Casadio et al., 2017; Périard et al., 2015).

The homeostatic mechanisms and physiological responses associated with thermal challenges are largely integrated, with physiological sensors, integrators, and organs all participating to defend homeostasis when exposed to heat stress (Akerman et al., 2016; Sawka et al., 2011). In an applied sense, the physiological targets for heat adaptation have high potential for modification. The variables; cardiac frequency, stroke volume, skin blood flow, sodium loss, body water loss, sweat rate, and urine flow can be assembled into five distinct groups of possible adaptations resulting from repeated heat exposures; 1) sweating and skin blood flow; 2) blood volume and fluid balance; 3) cardiovascular stability; 4) metabolic changes; and 5) perceptual changes (Périard et al., 2015; Tyler et al., 2016). Chapter 2.2 discusses the each of these physiological adaptations in further detail, along with considering how adaptation to heat can impact performance. Briefly, the adaptations (that occur in response to repeated and sufficiently stressful thermal impulses) and the outcomes that support exercise performance in the heat are outlined in Table 2-1.

Table 2-1: Heat acclimation adaptations and outcomes that support exercise performance in the heat.

Adaptation	**Outcome**
Core Temperature	
Resting	Decreased
Exercise	Decreased
Sweating	
Onset	Decreased
Rate	Increased
Sensitivity	Increased
Skin Temperature	
Exercise	Decreased
Skin blood flow	Increased
Fluid Balance	
Thirst	Better regulated
Electrolyte losses	Decreased
Total body water	Increased
Plasma volume	Increased
Cardiovascular stability	
Resting heart rate	Decreased
Exercise heart rate	Decreased
Stroke volume	Increased
Cardiac output	Sustained
Blood pressure	Sustained
Skeletal muscle metabolism	
Muscle glycogen	Spared
Lactate threshold	Increased
Muscle and plasma lactate	Decreased
Muscle force production	Increased
Whole body metabolic rate	Decreased

Adapted from Sawka et al. (2011)

In the literature to date, wide variability in heat acclimation protocols have been explored. Variations in protocol length (i.e., days of heat stimulus), duration of each stimulus, frequency of heat stimulus, heat acclimation mode (exercise-based or passive), exercise mode (i.e. cycling or running; weightbearing or non-weightbearing), passive heat acclimation mode (i.e. hot water immersion or sauna), exercise intensity, and wet-bulb temperature/environmental conditions (e.g. hot-humid vs. hot-dry) are all possible. While protocol length is commonly considered to be the most important consideration, physiological adaptations exhibit differing time-courses of induction; hence, modifying the duration, mode, or intensity of each stimulus all have the potential to stimulate different physiological adaptations (Akerman et al., 2016; Gibson et al., 2019a). Chapters 2.3 and 2.4 discuss the methods and length of heat acclimation stimuli in further detail.

Whilst heat acclimation adaptations can be induced rapidly (e.g., <5 days), subsequent decay in these adaptations also occurs over time once the heat stimulus is removed. Thus, reinduction and maintenance of heat acclimation adaptations is an important consideration for practitioners when incorporating heat acclimation strategies to their pre-competition training period. It is typically accepted that physiological adaptations resulting from heat acclimation decay at ~2.5% per day once a heat stimulus is removed (Daanen et al., 2018); however, the interaction between the variables associated with heat acclimation induction and the rate of decay is relatively un-explored. These concepts are further discussed in Chapter 2.5.

For athletes preparing to compete in hot climatic conditions, heat acclimation is considered to be the most important intervention to reduce physiological strain, and thus optimise performance (Racinais et al., 2015). However, implementing such protocols within an elite team-sport involves delicate consideration of other training priorities, along with individual differences within a team (Casadio et al., 2017). While this entire review is written with these applied considerations in mind, Chapter 2.8 discusses them in further detail.

While heat acclimation forms the most important heat management strategy, the application of acute cooling strategies to alleviate heat stress on the day of performance remain an important consideration for athletes and teams competing in the heat. These cooling strategies are typically characterised into either pre or per-cooling. Previous literature has investigated a multitude of strategies, with varying levels of effectiveness in a variety of athletic contexts. Chapter 2.10 discusses cooling strategies in greater detail, with a focus on summarising key findings that are particularly relevant to team-sport athletes competing in the heat.

The following review of literature is organised in a sequence that aims to give the reader an understanding of the rationale for the subsequent research. Within, the basic mechanisms of adaptation are briefly discussed. Given the population involved in the current thesis, and the stated purpose in Chapter 1.2, each section of the review is centred towards applied athletic performance, rather than complex mechanistic discussion and appraisal.

2.2 Physiological mechanisms of adaptation due to heat acclimation

2.2.1 Sweating and skin blood flow

Changes to the exercise sweat response form one of the principle physiological responses to heat acclimation (Klous et al., 2020; Taylor, 2014). Adaptations to the sweat response are both central and peripheral in nature and are integrated between many body systems (Périard et al., 2015). Centrally, heat acclimation initiates a shift in the onset of sweating, which occurs earlier during exercise and at a lower core temperature (Patterson et al., 2004a). This lower sweating threshold T_c is likely related to a decreased resting T_c, as similar changes in absolute T_c before sweating onset still seem to be evident (Patterson et al., 2004a). Meanwhile, morphological changes in the eccrine sweat glands are responsible for peripheral adaptations associated with the sweat response. These morphological changes, such as improved cholinergic sensitivity, eccrine sweat glad hypertrophy, and improved efficiency, act together to increase sweat rate in heat acclimated individuals (Tyler et al., 2016). In addition, eccrine sweat glands seem to develop a resistance to hidromeiosis following heat acclimation, resulting in the ability to sustain the developed higher sweat rate (Baker & Wolfe, 2020; Lorenzo & Minson, 2010).

Along with enhanced sweat rate, changes in sweat composition also occur (Buono et al., 2018). Typically, heat acclimation induces a decreased sodium concentration of sweat, along with greater resorption of sweat electrolytes (sodium, chloride) in the duct of the sweat gland, resulting in a more dilute sweat (Nadel et al., 1974b; Taylor, 2014). This sweat dilution can be beneficial in a number of ways; firstly, as electrolytes (solutes) lower the water vapor pressure at the skin for a given temperature, a more dilute sweat is more easily evaporated (assuming that the climate allows evaporation) because of widening of the water vapour gradient between skin and ambient air (Taylor, 2014). Secondly, having additional solutes within the extracellular fluid space will exert osmotic pressure on the intracellular space, thus redistributing fluid which is beneficial for cardiovascular stability when exercising in the heat (Sawka & Montain, 2000). Thirdly, an increased sweat sodium ion concentration has been shown to be one of the factors associated with the development of hyponatremia during prolonged exercise; thus, the resorption of sweat electrolytes protects against potentially catastrophic effects associated with exercise in the heat (Hew-Butler et al., 2015).

Fundamentally, blood flow to the periphery (skin) is responsible for transferring metabolic heat to the environment (Gonzalez-Alonso et al., 2008). During exercise in a hot environment, the temperature gradient between the body core and skin is less than in an temperate environment, such that skin blood flow must be relatively high to provide enough heat transfer to maintain thermal balance (Périard et al., 2016). In a non-heat adapted individual, the main difficulty with this high skin blood flow is the subsequent pooling of blood in the skin, resulting in a reduction in cardiac filling, causing subsequent physiological responses to defend cardiac stroke volume; including reductions in splanchnic blood flow, increased cardiac contractility, and increased heart rate for a given exercise intensity (Gonzalez-Alonso et al., 2008; Taylor, 2014). If these responses are insufficient, skin and muscle blood flow are likely to be impaired, possibly leading to hyperthermia, reduced exercise performance, and in extreme cases, symptoms of heat illness. Fortunately, the earlier and larger sweating potential resulting from heat acclimation acts to increase evaporative cooling (if under compensable heat stress conditions), and thus reduce skin temperature and requirements for skin blood flow. Other cutaneous adaptations such as a lower mean body temperature threshold (i.e. lower core and skin temperatures) for cutaneous vasodilation (Barry et al., 2020), along with local adaptations causing improved vasodilatory sensitivity, can also be attributed to the improvement in skin blood flow seen as a result of heat acclimation (Lorenzo & Minson, 2010).

Together, adaptations in sweat response, increases in evaporative cooling, and cutaneous adaptations resulting from heat acclimation act to minimise the impact of increased metabolic heat transfer requirements during exercise in the heat. These adaptations correspond with changes in blood flow to the periphery and allow for redistribution from the periphery to the central circulation and skeletal muscle, which further integrate with other circulatory adaptations, such as decreased heart rate during exercise (Périard et al., 2016; Rowell et al., 1967).

2.2.2 Blood volume and fluid balance

Exercise in the heat places a large reliance on blood (particularly plasma) volume resources, due to the independent effects of exercise and high body core temperatures (hyperthermia) that elicit acute plasma volume reductions. Hyperthermia produces this effect through sweat secretion, with primary sweat taken from the extracellular fluid, which includes both the intravascular and interstitial compartments (Patterson et al., 2014). Whereas at the onset of exercise, intravascular fluid moves into the intracellular compartment of the active skeletal muscles (Maw et al., 1998).

One of the most widely reported adaptations associated with heat acclimation is the expansion of plasma volume (Sawka & Coyle, 1999; Tyler et al., 2016). This expansion acts to support increased sweat rates, facilitate cooling and attenuate the rise in core body temperature and heart rate as discussed in Chapter 2.2.1. Reported plasma volume expansion is generally 4 to 15%, however, this can be highly individual, with the possibility of no expansion, or an increase of up to 27% also being reported (Patterson et al., 2014; Périard et al., 2015). The acute mechanism(s) responsible for this expansion are likely related to increased secretion of aldosterone (essential for sodium conservation) and arginine vasopressin (essential for fluid conservation), which ultimately function to retain sodium, decrease the glomerular filtration of the kidney, and decrease urine output; mediating an increase in extracellular fluid volume (Akerman et al., 2016; Convertino, 1991; Mack & Nadel, 2011).

As a longer-term adaptation, it has been hypothesised that exercise in the heat contributes to an increased synthesis of albumin, creating an increase in circulating proteins which drives up osmotic pressure within the blood vessel, functioning to further increase plasma volume (Kissling et al., 2020; Patterson et al., 2004b). A final behavioural mechanism that has been suggested to facilitate the rise in plasma volume is a maintenance of fluid balance via an increase in thirst (and hence water intake when available) following repeated bouts of exercise in the heat (Akerman et al., 2016).

Large robust changes in plasma volume have been reported with ~5 days of heat acclimation (Tyler et al., 2016). Ultimately, this expansion mediates many of the cardiovascular adaptations to heat acclimation and has two apparent physiological advantages: (a) increasing ventricular filling pressure and stroke volume, which allows cardiac output to be maintained with a reduction in heart rate during exercise in the heat (i.e. cardiovascular stability) (Rowell et al., 1967; Wyndham et al., 1968); and (b) increasing the specific heat of blood to slightly lower skin blood flow responses (Rowell et al., 1967; Sawka et al., 2011). The size of expansion in plasma volume exhibits large interindividual variability, shown to be dependent upon the technique and timing of the measurement, the number of heat exposures, and the size of the thermal impulse (Périard et al., 2015). Thus, even though the adaptations outlined above have been well described among the literature, caution is recommended when interpreting plasma volume expansion as a result of a heat acclimation stimuli due to this variability (Alkemade et al., 2021; Taylor et al., 2020).

2.2.3 Cardiovascular stability

The term cardiovascular stability is defined as the ability of integrated cardiovascular systems to defend cardiac output and mean arterial pressure, which are highly-regulated homeostatic variables (Gonzalez-Alonso et al., 2008; Taylor, 2014). This concept underlies many challenges of exercising in the heat, and as such, adaptations that improve cardiovascular stability are widespread, and integrated across many systems (Périard et al., 2016). It is widely accepted that adjustments during the early stages of heat acclimation are cardiovascular in origin (Périard et al., 2015; Taylor, 2014). The impaired ability to exercise in the heat is most often acutely linked to cardiovascular insufficiency, rather than hyperthermia; as such, any cardiovascular adaptations resulting from heat acclimation would be potentially very important to during exercise. Initially, during exercise in the heat, heart rate will be higher than equivalent exercise in temperate conditions. During subsequent sessions, heart rate will begin to decrease at a given workload; hence, it has been suggested that the clamping of heart rate may provide an alternative forcing function to the controlled hyperthermia approach to ensure appropriate physiological strain during heat acclimation protocols when the attainment of core temperature is not available (Travers et al., 2020; Tyler et al., 2016).

Improved cardiovascular stability can be demonstrated by the maintenance of cardiac output and arterial pressure, despite reductions in heart rate, due to compensatory increases in stroke volume (Senay et al., 1976; Tyler et al., 2016). It is suggested that this compensation occurs to stabilise mean arterial pressure and central venous pressure which are highly regulated homeostatic variables (Périard et al., 2016; Sawka et al., 2011). The mechanisms associated with reduced cardiovascular strain (increased cardiovascular stability) are largely integrated and play a role in many adaptations related with heat acclimation (Akerman et al., 2016; Périard et al., 2016; Sawka et al., 2011). These mechanisms include more efficient distribution of blood volume to the periphery (resulting in improved skin cooling), plasma volume expansion (as described above), increased venous tone from cutaneous and non-cutaneous vascular beds, reduced skin and core temperature, and a decrease in sympathetic nervous activity via decreases in circulating norepinephrine levels (Périard et al., 2015; Périard et al., 2016). As with most adaptations, the relative contributions of these variables will vary over the course of heat acclimation and among individuals (Sawka & Coyle, 1999). The characteristic cardiovascular adaptations induced as a result of heat acclimation are shown in Table 2-2.

Table 2-2: Cardiovascular adaptations associated with heat acclimation that led to improved cardiovascular stability

Cardiovascular parameter	**Adaptation**
Heart rate	Lowered
Stroke volume	Increased
Cardiac output	Better sustained
Blood pressure	Better sustained
Myocardial compliance	Increased
Myocardial efficiency	Increased
Cardio-protection	Increased

Adapted from (Sawka et al., 2011).

2.2.4 Whole-body and skeletal muscle metabolism

Depending on the muscular characteristics of any given exercise performance, exercising in the heat and subsequent elevations in muscle temperature result in changes to skeletal muscle metabolism and function that can either enhance or impact performance. For example, during short-duration exercise (i.e., sprinting), performance improves from 2 to 5% with a 1 °C increase in muscle temperature (Bergh & Ekblom, 1979; Racinais & Oksa, 2010). Mechanistically, muscle temperature increases are known to improve nerve conduction velocity, metabolic and contractile function, along with intramuscular conformational changes associated with contraction (Allen et al., 2008). In contrast however, if core body temperature increases beyond an individual's threshold (i.e., hyperthermia), this positive relationship ceases, and performance may become impaired. Specifically, environmental heat stress is associated with elevated muscle temperatures and a faster rate of fatigue (Hargreaves, 2008) leading to detrimental effects on exercise performance in both endurance (Edwards et al., 1972), and repeated sprint contexts (Drust et al., 2005).

In general, exercise in the heat is characterised by higher anaerobic strain whereby substrate utilisation is shifted towards greater carbohydrate and decreased fat use (Febbraio, 2001). As such, muscle glycogen utilisation and anaerobic metabolism are increased, causing a greater accumulation of ammonia and muscle lactate (Febbraio, 2000; Febbraio et al., 1994). In turn, high glycolytic rates are associated with an increased release of hydrogen and inorganic phosphate ions (Robergs et al., 2004). The accumulation of hydrogen ion acts to lower the internal pH which has downstream effects such as interfering with the release of calcium ion from the sarcoplasmic reticulum, resulting in impaired cross bridge cycling and impaired muscle force (Allen et al., 2008; Wan et al., 2017). Meanwhile, increased inorganic phosphate ions act to impair myofibrillar performance and the release of calcium ion from the sarcoplasmic reticulum, thus contributing to decreased muscle activation (Allen & Trajanovska, 2012).

There is some evidence that heat acclimation can result in alterations in whole body and skeletal muscle metabolism, with heat acclimation having a moderate effect on lowering the oxygen cost of a given exercise intensity (Tyler et al., 2016). In turn, muscle glycogen utilisation and lactate accumulation (in the blood and muscle) have been shown to be reduced as a result of heat acclimation (Febbraio et al., 1994). The mechanisms responsible for these adaptations are unclear; however, it has been suggested that heat acclimation may reduce the rate of glycogenolysis or reduce the aerobic metabolic rate and change lactate kinetics. Alternatively, the increase in central blood volume induced by heat acclimation may help to increase hydrogen ion removal and buffering (Febbraio et al., 1994). Together, these adaptations act to decrease the metabolic stress at a given work output, along with improving exercise efficiency, resulting in a decreased heat production or ability to sustain a higher power output; thus, improving exercise performance.

2.2.5 Perceptual changes

The large majority of heat acclimation research is focussed on improvements in physiological indices that allow for improved exercise performance and capacity, with psychophysical improvements, such as perception of effort (RPE), thermal sensation, and thermal comfort often being overlooked (Tyler et al., 2016). However, it has previously been suggested that attenuating thermal discomfort is as important as the well-defined physiological responses to heat acclimation and can result in exercise performance improvements (Cheung, 2010). In turn, heat acclimation may result in a learned internal experience, such that the perception of sensations from inside the body could explain the differences in final T_c seen at the point of voluntary exhaustion in athletes of different training status (Selkirk & McLellan, 2001). This internal sensation perception may also explain the consistency seen in T_c at the point of voluntary exhaustion, despite experimental manipulations such as starting T_c (Cheung, 2010; Gonzalez-Alonso et al., 1999).

Of the limited studies that have addressed perceptual measures, it does seem that heat acclimation can reduce the RPE during subsequent bouts of exercise in the heat (Neal et al., 2016). Most recently, Zurawlew and colleagues (2018) showed that end exercise RPE and thermal sensation were lower during a heat response test following a heat acclimation protocol in both endurance-trained and recreationally active individuals. These perceptual indices can play a key role in improving exercise performance (i.e. a reduction in RPE should enable individuals to self-select a higher work load during a performance) and capacity (i.e. an individual should be able to tolerate steady-state exercise for longer) in the heat (McCormick et al., 2015).

Perception of thermal comfort is a key driver of volitional behaviour in the heat and is heavily influenced by past and concurrent experiences (Taylor, 2014). For instance, it is considered that changes in skin temperature are the main driver of thermal sensation, while thermal comfort is influenced by core temperature, and it is their combination that is evaluated from the perspective of overall tolerance. In this regard, one individual can feel hot but comfortable, while another may express equal warmth but describe the sensation as uncomfortable (Taylor, 2014). Any mechanisms responsible for these psychophysical improvements due to heat acclimation are difficult to elucidate; however, it is likely that they are related to underlying physiological adaptations, and that undertaking heat acclimation improves thermal comfort by shifting thermal sensations to greater levels of physiological strain (Périard et al., 2015; Tyler et al., 2016). In this regard, it may be suggested that athletes, particularly those of elite standard, may have greater underlying resilience to thermal impulses compared to recreational and/or sub-elite athletes due to their training history and experience sustaining greater physiological indices.

2.2.6 Performance outcomes resulting from heat acclimation

Collectively, the physiological mechanisms associated with adaptations to heat outlined in Chapter 2.2 provide the integrative framework upon which performance in the heat is improved when heat acclimated. For example, heat acclimation has been demonstrated to improve maximal oxygen uptake and anaerobic threshold (James et al., 2017; Lorenzo et al., 2010), and most relevantly to endurance sports, improve exercise capacity and tolerance during exercise in the heat (Burk et al., 2012; Garrett et al., 2012; James et al., 2017; Keiser et al., 2015). Underscoring these findings from primary research, the meta-analysis of Tyler and colleagues (2016) outlined that heat acclimation can enhance endurance capacity under heat stress (time to exhaustion) by ~23% and time-trial performance under heat stress by ~7%. While most heat acclimation investigations have been concerned with prolonged, endurance-based performances, some investigations into field-based team-sports have also occurred. Collectively, these have demonstrated the efficacy of heat acclimation to improve repeated intermittent exercise tasks, along with heat tolerance (Buchheit et al., 2011; Castle et al., 2011;

Duvnjak-Zaknich et al., 2019; Pethick et al., 2019; Racinais et al., 2014; Sunderland et al., 2008). Unlike the current evidence presented in endurance sports, these team-sport investigations lack any ecologically valid control comparisons. Hence, practitioners in an elite team-sport context should be mindful when comparing responses in elite athletes to experimental data, as these are likely collected on less well-trained individuals with no control comparison (Gibson et al., 2019a). Further discussion of the applied considerations for elite team-sports are presented in Chapter 2.8.

2.3 Methods of heat acclimation

Over the past century, increased understanding of the stimulus required to induce adaptation to heat has developed. Classically described research from mining provided evidence of adaptations that resulted in increased work capacity when consecutive heat exposures were combined with physical work (Wyndham & Strydom, 1969). This work, along with early laboratory-based heat acclimation (HA) studies by Fox et al. (1963) provided initial understanding of the stimulus required to induce adaptation to heat so that work could be performed safely. More recently, a plethora of research has investigated varying approaches to HA, the majority of which has been concerned with endurance athletes. In this research, HA induction has been described using many strategies to provide the thermal stimulus to induce adaptations; namely: self-paced exercise; constant work-rate exercise; controlled hyperthermia; controlled heart rate; passive heating; and post-exercise passive heating (Périard et al., 2021; Périard et al., 2015; Taylor, 2014; Tyler et al., 2016). These strategies are briefly reviewed below, with a schematic overview given in Figure 2-1.

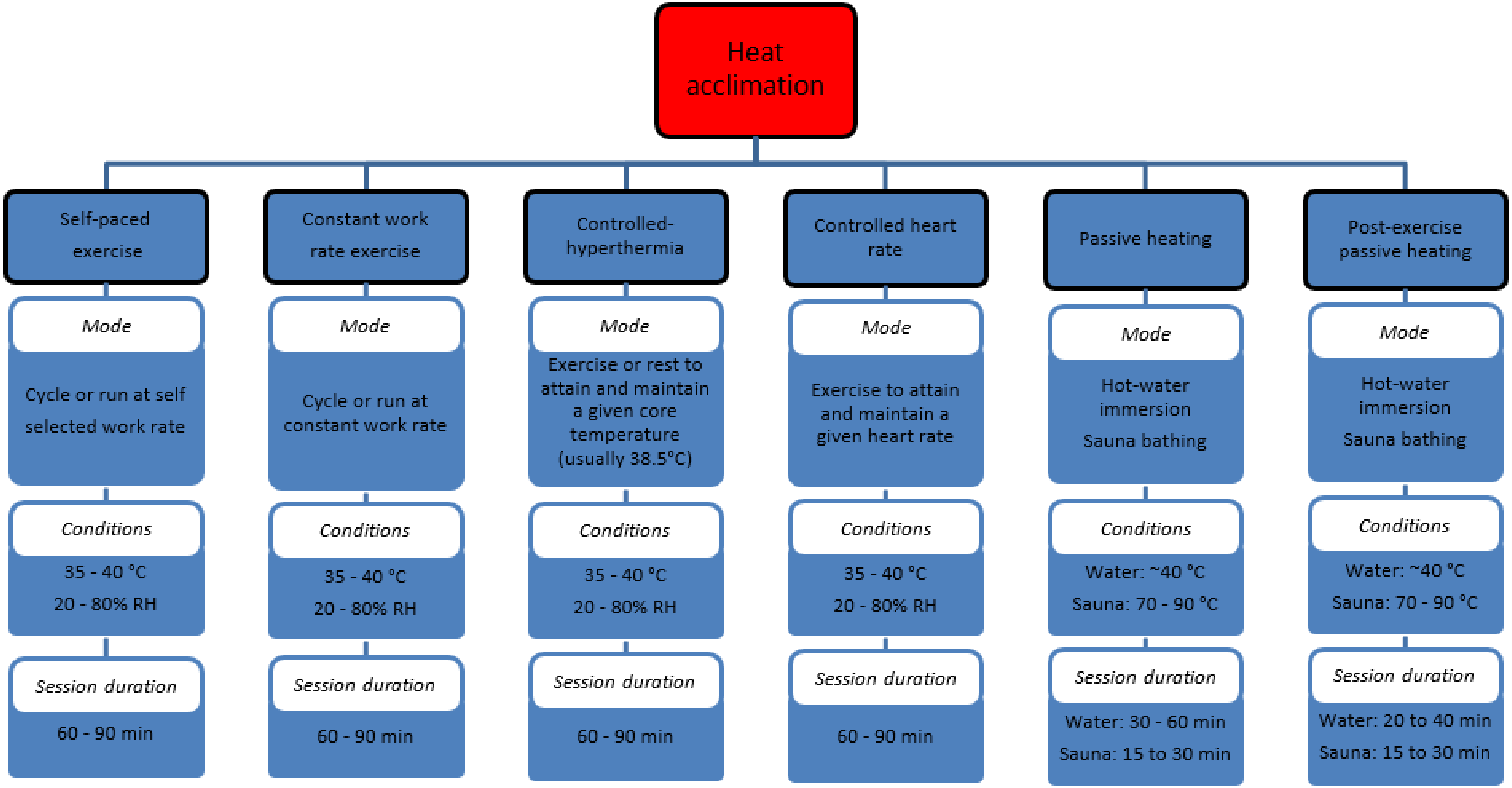


***Figure 2-1**:* Graphic overview of the common methods, modes, activity, conditions, and durations used for heat acclimation among previous literature. Adapted from Daanen et al. (2018).

2.3.1 Self-paced exercise

The self-paced exercise HA method is likely the easiest for practitioners to administer, as it involves simple monitoring techniques and gives individuals the ability to control their effort based on the integration of objective measures such as heart rate and time, as well as subjective perceptual cues like the perception of exertion, thermal comfort, and sensation (Périard et al., 2021). Indeed, self-paced exercise HA was originally used by the military to ensure the safety and preparation of large and diverse groups of un-acclimatised soldiers for rapid deployment to hot environments (Nelms & Turk, 1972). In turn, this method can be beneficial for team sports (Racinais et al., 2014), particularly during outdoor training camps (Buchheit et al., 2011) if local environmental conditions allow for an adequate thermal stimulus. Although the self-paced exercise HA method is easy and practical in some contexts, there are limitations in standardising the adaptation stimulus within and between training sessions, due to both inter- and intraindividual differences. Most self-paced exercise HA regimes have been performed in hot outdoor environments, whereby standardising the environmental conditions is impossible; moreover, this is not viable in temperate climate countries.

2.3.2 Constant work-rate

Similar to self-paced HA, the constant work-rate HA method was first used in occupational and military settings (Lind & Bass, 1963; Wyndham et al., 1968). As the name suggests, it involves participants exercising at a fixed-load in the heat (e.g., cycling at a specified target power output). In the literature, constant work-rate HA has been demonstrated to facilitate thermoregulatory, cardiovascular, metabolic, and cellular adaptations, the culmination of which provide improvements in work capacity under heat stress (Daanen et al., 2018; Febbraio et al., 1994; Poirier et al., 2015). This method has also been shown to improve time-trial performance (Lorenzo et al., 2010) and intermittent sprinting in the heat (Castle et al., 2011). Given the apparent efficacy, ease of use, and athlete familiarity with this type of exercise, it is a popular choice for practitioners; however, it is not without its limitations (Taylor & Cotter, 2006; Tyler et al., 2016). Most notably, as physiological improvements in heat transfer occur with adaptation over the course of a HA intervention, heat storage and the relative intensity of the exercise gradually decrease, thus causing a decreased thermal impulse (Fox et al., 1963; Taylor, 2014). With this reduction in thermal strain, physiological overload will decrease, resulting in familiarisation, which in an athletic context, has the potential to result in sub-optimal adaptation. Additionally, constant work-rate HA has high variability between individuals and protocols due to the different adaptation impulses, making any grouped interpretation of results difficult (Taylor et al., 2020; Tyler et al., 2016). Therefore, for an athlete seeking optimal adaptation, a constant standard thermal impulse is necessary to reduce this variability. As such, the use of the controlled hyperthermia technique is now most common in research (Taylor, 2014; Tyler et al., 2016). However, it has recently been demonstrated that a constant thermal impulse can be provided by increasing the ambient temperature by 1 °C each week during prolonged (5 weeks) exercise-based HA (Mikkelsen et al., 2019). The authors reported that rectal temperature was similarly elevated at the end of all cycling training sessions. The meta-analysis of Tyler and colleagues (2016) also indicated that constant work-rate HA provides a similar magnitude of improvement in exercise performance to that of controlled hyperthermia HA. Similarly, a direct comparison between these two HA approaches found that controlled-hyperthermia did not provide greater adaptations than constant work-rate exercise (Gibson et al., 2015a; Gibson et al., 2015b). Therefore, it appears that constant work-rate HA is a practical and effective means of inducing adaptations to the heat.

2.3.3 Controlled hyperthermia

Controlled-hyperthermia HA (or isothermic HA), was initially developed by Fox and colleagues (1963) in an effort to describe the internal adaptation stimulus based on a physiologically controlled variable, rather than the characteristics of the environment to which participants were exposed (Taylor et al., 2020). As mentioned in Section 2.3.2 above, the use of controlled-hyperthermia HA is most commonly used among physiological literature (Taylor, 2014; Tyler et al., 2016). The method involves clamping core temperature, usually at ~38.5 °C, thus exposing individuals to a constant thermal impulse, despite adaptations in thermoregulatory variables occurring throughout an HA protocol (Gibson et al., 2019a). This forcing function optimises adaptation via an increase in exercise capacity during subsequent heat exposures (Gibson et al., 2015b). The controlled-hyperthermia HA method has been demonstrated to induce a similar extent of adaptation as the constant work-rate protocol (Tyler et al., 2016), along with maintaining plasma volume expansion (an adaptation that is lost during 10 to 12-days of constant work-rate exercise in the heat) (Gibson et al., 2015b; Patterson et al., 2014). It has also been suggested that the controlled-hyperthermia HA method improves subsequent self-paced performance in the heat (Garrett et al., 2012) and reduces the physiological cost of attaining a magnitude of adaptation via the constant work-rate method (Gibson et al., 2015b).

If the facilities and knowledge are available, completion of a controlled-hyperthermia HA protocol can appeal to athletes and practitioners as the greater level of control can reduce disruptions to training, or training overload, compared to the implementation of constant work-rate protocols (Gibson et al., 2015b). In turn, controlling T_c is beneficial during passive HA protocols. Unfortunately, controlled-hyperthermia HA methods are labour and resource intensive and traditionally involve rectal or esophageal thermometry which are unpractical to deliver in many contexts (such as a team sport or large groups), and require trained practitioners for adequate T_c measurement. In turn, access to an artificially hot environment is required and the completion of the such protocols act to increase training load, which may negatively impact the quality of an athlete's training if the programme is not altered accordingly (Meeusen et al., 2013). These factors reduce the practicality of implementing such protocols (Périard et al., 2017). In this regard, a number of previous reviews have suggested that if T_c measurement is unpractical, using heart rate as a physiological forcing function may be a practical method of ensuring an appropriate physiological strain is maintained, due to the response of heart rate to HA (Gibson et al., 2019a; Périard et al., 2015; Tyler et al., 2016).

2.3.4 Controlled heart-rate exercise

As outlined in Section 2.3.3 above, using heart rate as a controlled variable has recently been established as an alternative approach to controlled-hyperthermia HA. In a sense, this method is a hybrid of the controlled work-rate HA method, as the adaptive stimulus is regulated by manipulating work rate to maintain a heart rate at a given range (Périard et al., 2021). The principle of the controlled heart-rate HA method is that the work rate (and hence the level of thermal strain) within each HA session corresponds to an individual's heart rate during exercise in ambient conditions (i.e., 75% $\dot{V}O_{2max}$ HR). Consequently, such control provides a constant stimulus for adaptation as the absolute work rate required to maintain a given heart rate increases as HA adaptations develop.

A recent example of such methods comes from Travers and colleagues (2020). The authors demonstrated that the cycling power output required to hold a heart rate equivalent to 65% $\dot{V}O_{2max}$ during the last 75 min of a 90-min session in 40 °C and 40% RH increased by ~15% throughout a 10-day HA protocol. The authors also demonstrated a maintenance of rectal temperature (~38.4 °C) during the last 75 min of the 90-min cycling session under these controlled heart rate conditions. Furthermore, other studies that have used the controlled heart-rate HA model to induce HA, have demonstrated many typical HA adaptations such as: decreased exercise core temperature at a given work rate, decreased exercise heart rate at a given work rate, increased sweat output, plasma volume expansion, enhanced evaporative heat loss, and improved time trial performance under heat stress (Keiser et al., 2015; Philp et al., 2017; Ravanelli et al., 2019). Taken together, these recent findings suggest that the controlled heart-rate HA method may provide practitioners and athletes with an efficient, practical, and familiar method of HA training. However, Taylor and colleagues (2020) noted many caveats of the controlled heart-rate HA approach. The authors suggested that focussing upon physiologically-controlled, rather than homeostatic-regulated variables (e.g. heart rate vs. core temperature), represents an experimental simplification with clear, and sometimes unanticipated and undesirable consequences when it comes to experimental interpretations.

2.3.5 Passive HA methods and post-exercise passive HA methods

Passive HA methods involve repeated 30-90 min exposures to heat, normally provided by hot water immersion (HWI) or sauna bathing (Heathcote et al., 2018). The emergence of these passive methods of HA are in part, due to practical/logistical constraints that preclude traditional exercise-based methods being used, particularly within elite/professional sporting contexts (Gibson et al., 2019a) (as discussed in Section 2.8 below). Such methods give practitioners and athletes the ability to save mechanical load for specific training modalities, and have been shown to be particularly effective when performed immediately after a temperate training session (Heathcote et al., 2019; McIntyre et al., 2021; Zurawlew et al., 2018; Zurawlew et al., 2016). The thermoregulatory advantages of passive HA have been well-demonstrated and are similar in adaptation response to exercise-based HA. For example, a decrease in heart rate and rectal temperature and an increase in sweat rate during exercise at a given work rate in the heat has been shown (Brazaitis & Skurvydas, 2010). Additionally, passive HA methods have been shown to lower the onset threshold for sweating and increase sweat sensitivity (Bailey et al., 2016), and improve skeletal muscle contractility and function (Racinais et al., 2017). Despite the demonstrated thermoregulatory advantages of passive HA, the performance advantages of such methods are unclear. Bailey and colleagues (2016) indicated that passive HA can increase $\dot{V}O_{2peak}$ in temperate conditions; however, it remains undetermined whether this approach can lead to improvements in exercise capacity under heat stress.

Compared to passive HA methods, the development of sport-specific adaptations contributing to improved performance are more likely while undertaking exercise-based HA protocols that replicate the work rate and environmental conditions in which competition will occur (Gibson et al., 2019a; Guy et al., 2015). However, highly-trained athletes have a well-developed aerobic capacity, hence, thermoregulatory adaptations that are perceptual in nature may be sufficient to enhance performance in the heat for such populations. While such perceptual changes have been demonstrated using passive HA methods in the literature (Heathcote et al., 2018), the impact on subsequent athletic performance is yet to be adequately evaluated.

To induce HA adaptations in an athletic setting, the use of passive heat exposures immediately post exercise is more frequently used than passive HA alone (Heathcote et al., 2018). This approach allows athletes to concurrently maintain a strong training impulse and induce HA, without the associated heat stress impacting upon training quality. The concept is that a normal training session naturally exhibits a rise in T_c that can be further exacerbated by adding passive heat stress to the end of a training session. These methods are particularly useful for elite and professional training programs as they are time efficient and preserve exercise-based training load, while overcoming many of the aforementioned limitations/barriers that other HA protocols present (Casadio et al., 2017). In turn, post-exercise passive HA methods have been demonstrated to elicit similar magnitudes of thermoregulatory and cardiovascular adaptations seen in exercise-based HA protocols (Zurawlew et al., 2016).

Of the examples of post-exercise sauna exposure Scoon and colleagues (2007) reported increases in plasma volume following a long-term protocol (~31 min per day for 3 weeks) in trained athletes. Correspondingly, Stanley and colleagues (2015) demonstrated ~30 min of sauna bathing immediately post normal daily cycling training, induced moderate-to-large increases in plasma volume after only four exposures. In a novel series of studies, Zurawlew and colleagues demonstrated that undertaking 6 consecutive ~40 min HWI (40 °C) sessions following the completion of 40 min running at 65% $\dot{V}O_{2max}$, HWI resulted in lowered T_c and T_{skin}, heart rate, RPE, and thermal sensation in both endurance-trained and recreationally active individuals during a 40 min run in the heat (Zurawlew et al., 2018; Zurawlew et al., 2016). These authors went on to demonstrate that much of the thermoregulatory and perceptual adaptations were retained for two-weeks after the HA protocol, with no further heat stimulus (Zurawlew et al., 2019). Most recently, McIntyre and colleagues (2021) performed a direct comparison of 6 days of post-exercise HWI vs. exercise-based HA induction methods in recreationally active males. These researchers found that post-exercise HWI elicited larger thermal adaptations compared with exercise-based HA, exhibited by lower resting rectal temperature following post-exercise HWI (-0.38 °C) compared to exercise-based HA (-0.14 °C), which translated to a lower end-exercise rectal temperature (-0.47 °C) during a subsequent exercise heat stress test (McIntyre et al., 2021).

When it comes to performance changes associated with post-exercise passive HA methods, the study by Zurawlew and colleagues (2016) demonstrated a ~5% improvement in 5-km treadmill running time-trial performance in in hot, but not cool conditions following post-exercise HWI. The study of Scoon and colleagues (2007) demonstrated a 32% increase in run time to exhaustion in cool conditions, equivalent to a ~2% improvement in 5-km running time trial performance. In contrast, McIntyre and colleagues (2021) reported no differences in time to exhaustion (running at 65% $\dot{V}O2_{peak}$) in the heat (33 °C, 40% RH) between post-exercise HWI and exercise-based HA methods.

Although there is limited evidence, particularly in elite and/or professional sporting context, it appears that post-exercise passive HA methods can provide a practical and time-efficient method to induce HA. However, an important consideration when using post-exercise passive HA methods is that the heat session should commence immediately after training (within 10 min) to maximise acute T_c and heart rate responses (Heathcote et al., 2019).

2.4 Length of heat acclimation stimulus

In the literature to date, approaches to HA induction have had a large amount of variation in terms of their thermal stimulus. Variations in time (successive days of exposure and the length of each stimulus) have been well described, with HA protocols being classified into either short-term (STHA; 4 to 7 days), moderate term (MTHA; 8 to 14 days), or long term (LTHA; ≥ 15 days) (Garrett et al., 2011; Gibson et al., 2019a). Ultimately, the magnitude of adaptation depends on a combination of the intensity, duration, frequency, and number of heat exposures (i.e., the cumulative thermal impulse) (Périard et al., 2015; Taylor, 2014).

It is well established that acquiring tolerance to the heat is a sequential process, with the rate of adaptation differing between variables, whether they be physiological or perceptual (Périard et al., 2015; Taylor, 2014; Tyler et al., 2016). As such, most early research suggested that exercise-based, MTHA to LTHA provided optimal adaptation and improved exercise capacity and performance in the heat, as they allowed sufficient time for multiple adaptations to occur (Casadio et al., 2017; Gill & Sleivert, 2001). However, recent evidence suggests that extending the number of HA exposures may not increase the magnitude of induced adaptation, as most performance enhancing adaptations, such as an expansion in plasma volume and reductions in exercising heart rate and T_c, occur during STHA (Tyler et al., 2016). Therefore, it has been suggested that when the time to acclimate is limited, or when minimal disruptions to pre-competition training is required, the completion of more than seven exposures may be unnecessary (Garrett et al., 2012; Garrett et al., 2011; Tyler et al., 2016). The effectiveness of STHA was demonstrated by Garrett and colleagues in a series of studies showing that 5 days of controlled-hyperthermia HA induced adaptations that reduced thermal and cardiovascular strain during exercise-heat stress (Garrett et al., 2012; Garrett et al., 2014; Garrett et al., 2011). In addition, five controlled-hyperthermia HA sessions have been demonstrated to initiate a moderate reduction in core body temperature at rest, which is one of the key elements of HA induction (Gibson et al., 2015b; Neal et al., 2016). Together, the adaptations demonstrated as a result of performing exercise-based STHA suggest that when the thermal stress is sufficiently high during HA exposures, the number of sessions that are required to elicit optimal adaptation may be reduced.

While the argument for STHA has developed momentum over recent years, particularly for highly-trained athletes (Gibson et al., 2019a), the meta-analysis of Tyler and colleagues (2016) noted that medium to long-term HA protocols tend to provide more robust improvements in performance than STHA protocols (Tyler et al., 2016). In turn, consensus recommendations by Racinais and co-authors (2015) regarding training and competing in the heat, based on extensive literature over several decades stated that “HA should be comprised of daily ~60 min training sessions in hot conditions for a minimum of one week, and ideally over two weeks, to achieve optimum thermoregulatory and performance benefits”. The authors of this review go on to suggest that the HA protocol should endeavour to mimic the physiological demands of the athletic event and be in the environment in which they will be competing, to induce physiological adaptations that are relevant to an athlete’s circumstances (Racinais et al., 2015). Although such recommendations provide an excellent framework for practitioners to develop a HA protocol relevant to their athletic situation, the practicalities around integrating a sport-specific protocol into an elite athletes existing training program are somewhat ignored. In this regard, the reviews of Pryor and colleagues (2019a) and Gibson and colleagues (2019a) each provided some generic recommendations for the application of HA strategies in both endurance and team sport contexts, however, these recommendations are based on little evidence in applied elite sport settings.

2.5 Decay and re-acclimation of heat acclimation

Information regarding the induction of physiological and perceptual HA adaptations is extensive. However, these adaptations are transient and are known to recede following the subsequent removal of a heat stimulus (Daanen et al., 2018; Pandolf, 1998; Weller et al., 2007). It is suggested that the adaptations occurring first, which are cardiovascular in nature, such as an expansion in plasma volume and a reduction in exercising heart rate, also demonstrate the most rapid decay (Flouris et al., 2014; Taylor, 2014). Knowledge regarding HA adaptation decay is currently limited and explanations for the differences in the literature are in part, due to a lack of consistency between experimental designs, small sample sizes, and/or inappropriate measures (Daanen et al., 2018; Pandolf, 1998).

From a recent meta-analysis of 12 studies, it was evident that HA decay and heat re-acclimation differ considerably between physiological systems (Daanen et al., 2018). The available literature to date has many confounding methodological issues such as the heat exposure type, training status, and duration of acclimation, making certain conclusions regarding adaptation decay difficult. Notwithstanding the lack of standardisation among the studies analysed, the authors went on to make the broad suggestion that for every decay day, ~2.5% of the adaptations in heart rate and core temperature are lost. Notably, none of the studies included in the analysis of Daanen and colleagues (2018) included team-sport athletes, which may impact the transferability of findings to such athletes, particularly considering that the articles included in the analysis were mostly in low to moderately trained individuals. More recently in moderately-trained team sport athletes, Duvnjak-Zaknich and colleagues (2019) indicated that prolonged repeat-sprint exercise performance in the heat is well-maintained over two subsequent weeks, despite heat stimulus removal, following either intermittent (8 sessions over 15 days) or consecutive HA (8 sessions over 8 days).

Daanen and colleagues (2018) indicated that heat re-acclimation induces adaptations in heart rate and core temperature at a faster rate than HA, particularly when undertaken within a month of the initial HA stimulus. They went on to suggest that since the physiological adaptations in heart rate and core temperature occur much faster during re-acclimation, it can be expected that the decay in these variables can be fully compensated with ~4 days of re-acclimation. For adaptations such as sweat rate that initially take longer to materialise, the period of re-acclimation may need to be extended to achieve an acclimation status greater than that occurring during the initial induction period (Saat et al., 2005). The best method of fully augmenting these slower adaptations may be by planning to arrive early at a competition venue to take advantage of the local climate; however, that approach may be limited by various considerations such as other competitions, financial aspects, and facilities at the destination (Casadio et al., 2017). Additionally, due to the inherent unpredictability of weather, early arrival at a competition does not guarantee that a sufficient heat impulse will be experienced (unlike hypoxia for example). In this regard, planning for heat re-acclimation may provide a practical, less disruptive, and guaranteed means of maintaining and optimising adaptations to the heat immediately prior to competition, whilst still allowing for appropriate training/taper that may be necessary for the athletes.

Recently, Gerrett and colleagues (2021) found that, after a successful 10-day controlled-hyperthermia HA protocol, most acquired physiological adaptations were retained during a 28-day decay period. These researchers did observe that sudomotor adaptations were lost during the decay period; however, these adaptations could be reinstated with 5-days of either active or passive HA. These data led the researchers to suggest that in habitually trained individuals, heat re-acclimation may not be necessary within a 28-day decay period, providing that the initial thermal HA impulse was sufficient to elicit robust adaptations (Gerrett et al., 2021). These findings are particularly important for practitioners aiming to schedule HA into a pre-competition period, and provides support for the notion that aerobic fitness and regular exercise across the decay period contribute to maintain adaptations or reduce the rate of decay (Périard et al., 2021; Weller et al., 2007). Given the described evidence of HA decay and re-acclimation, practitioners need to choose an approach based on their scheduling demands. It seems that practitioners have the choice between a small initial thermal impulse with frequent top-up exposures, or alternatively a large initial thermal impulse with less requirement for top-up exposures. Hence, providing that practitioners are equipped with this background knowledge, they should be able to make informed decisions based on their specific circumstances.

2.6 Sex differences in responses to heat stress

Historically, researchers had believed that thermoregulation in females was less efficient compared to males, stemming from observations that core body temperature was higher among women for a given exposure (Druyan et al., 2012; Epstein et al., 2013; Yanovich et al., 2020). Despite this assertion, Gagnon and Kenny (2012) reported similar responses to heat stress in males and females when the rate of metabolic heat production is appropriately fixed. During tasks without a fixed internal load, however, individual variability in temperature regulation is mainly due to morphological and fitness-related characteristics altering the components of heat balance (internal heat generation and external heat dissipation), rather than "sex differences" *per se* (Notley et al., 2019).

During exercise, muscle mass primarily dictates the amount of heat generated, while the amount of heat dissipated is based on body surface area (Taylor, 2014). Consequently, with an increase in muscle mass there is a concomitant increase in heat generation (and vice-versa); while a decrease in surface area-to-mass ratio (i.e., bigger body size) results in less heat transfer to the environment (providing that environmental conditions allow for heat transfer) (Taylor, 2014). Compared to males, females averagely have a smaller body mass (and subsequently, a smaller body surface area), higher body fat mass, and a larger surface area-to-mass ratio (Cheuvront & Haymes, 2001; Yanovich et al., 2020). Therefore, when males and females with similar aerobic ability are compared, the sex-based difference in surface area to-mass ratio may be an advantage for females, particularly those in endurance type events that have a large reliance on maintaining heat balance (Cheuvront & Haymes, 2001). Of further benefit, females exhibit a higher density of sweat glands in many areas of skin, use a higher percentage of their sweat glands (Gagnon et al., 2013a), and secrete less total sweat (Baker et al., 2020). This overall increase in sweating efficiency may decrease wasted sweating, where secreted sweat drips off the body without evaporating. This wasted sweating is more likely to occur in a humid environment, where the absolute vapor pressure gradient for sweat evaporation is decreased (Moyen et al., 2014). For example, Shapiro and colleagues (1980) evaluated thermoregulatory responses of men and women exercising in temperate (20°C, 40% RH), hot/humid (~36 °C, 85% RH) and hot/dry (~55 °C, 15% RH) conditions. These authors found that T_c increased less in females than in males for hot/humid environments, and vice versa in hot/dry conditions. As a result of their data, the authors went on to suggest that the larger surface area-to-mass ratio in women, along with more efficient sweating suppression in humid conditions, allowed women to tolerate the hot/humid environments better than men. In contrast, the higher overall sweating capacity in men allowed them to respond more efficiently to the dry heat (Shapiro et al., 1980).

In females, the thermoregulatory system is in a continuous state of change across the menstrual cycle due to influences of the reproductive hormones estrogen and progesterone (Charkoudian & Stachenfeld, 2016; Yanovich et al., 2020). Resting T_c changes during the menstrual cycle; being ~0.3 – 0.5 °C higher when progesterone and estrogen are elevated (in the midluteal phase) compared with the early follicular phase when both hormones are relatively low. Additionally, small decreases in resting T_c have been shown during the preovulatory phase, when estrogen is elevated unopposed by progesterone (Stephenson & Kolka, 1999). These hormone mediated changes in T_c are also associated with modifications to the onset thresholds and sensitivity of autonomic heat loss responses, such as sweating and cutaneous vasodilation (Charkoudian & Stachenfeld, 2016; Yanovich et al., 2020).

There is ongoing discussion about whether the documented influences of reproductive hormones on thermoregulatory mechanisms in women result in quantifiable differences between the sexes in the capacity to dissipate heat (Charkoudian et al., 2017). A recent meta-analysis observed a small but significant increase in post-exercise T_c following aerobic exercise in the heat in the luteal phase of the menstrual cycle compared to the follicular phase (Giersch et al., 2020). However, the authors went on to suggest that the limited data availability, and the poor validity of some of the included studies meant that the certainty of this conclusion was not without reservation. Thus, it remains largely undetermined if sex-based differences relating to the sudomotor function and the menstrual cycle make females more susceptible to performance deficits in the heat (Corbett et al., 2020; Hutchins et al., 2021).

Historically, females are underrepresented among thermoregulation literature (Hutchins et al., 2021). For example, females only accounted for 30% of the total participants in exercise thermoregulation literature in 2019. Appropriately controlling for contraceptive use, hormonal status, or menstrual cycle can require considerable additional time and resource across the course of a thermoregulation research project. These factors have likely contributed to the lack of females in previous work (Sims & Heather, 2018). When females are present within a study, despite limited and conflicting data on the effect of the menstrual cycle on thermoregulatory functions, less than 30% of articles reported women’s menstrual orientations (i.e., naturally menstruating, hormonal contraceptive user, pregnant, postmenopausal, oligomenorrheic, secondary amenorrhoeic cycles), and only 22% reported both menstrual orientation and phase, making conclusions difficult (Hutchins et al., 2021).

2.7 Sex differences in responses to heat acclimation

Although the benefits of HA have been well established, data concerning best-practise HA in females remains scarce. Consequently, female athletes typically implement HA strategies that are based upon methods researched in male athletes, which may result in only partial or sub-optimal adaptations (Mee et al., 2015). Historical research comparing male and female responses to HA have used prolonged low intensity exercise, indicating that the responses to acclimation were similar despite men having higher sweat rates than women (Avellini et al., 1980; Horstman & Christensen, 1982; Shapiro et al., 1980). Following this, Sunderland and colleagues (2008) demonstrated that four 30 to 45 minute sessions of intermittent exercise induced acclimation (STHA), and resulted in an improvement in intermittent running exercise capacity in female games players. These authors suggested that the lower early exercise T_c (by ~0.2 °C) and associated increase in thermal comfort were (partly) responsible for the improvement in exercise capacity. These results are questionable, however, as the reliability of the repeated shuttle run performance test employed by Sunderland and colleagues (Loughborough Intermittent Shuttle Test) is subject to greater variation than a self-paced performance test (Borg et al., 2018). Furthermore, time to exhaustion tests do not allow for the behavioural regulation of performance possible in a self-paced time trial (Schlader et al., 2011c).

More recently, a robust investigation by Mee and colleagues (2015) suggested that females exhibit a different temporal pattern of HA adaptation induction, noting that STHA resulted in an increase in sweat rate despite no changes in cardiovascular and thermoregulatory response in females, compared to males. The authors went on to conclude that females required LTHA to establish thermoregulatory and cardiovascular stability. In addition, they suggested that the controlled hyperthermia method may constrain adaptation in females compared to males, due to a lower metabolic heat production and thus lower evaporative requirements during the HA session (Mee et al., 2015). As mentioned in Section 2.4, and further detailed below in Section 2.8, STHA provides the most attractive HA model, as it incurs less disruption to training prior to competition. Nevertheless, STHA may not provide an adequate thermal impulse to elicit optimal adaptations in females. In this regard, it has been suggested that for female athletes, a combination of passive heat and controlled hyperthermia heat exposures may accelerate adaptation (Mee et al., 2018; Zurawlew et al., 2018).

This concept was followed up by Mee and colleagues (2018) whereby the use of 20-min sauna pre-heating, prior to each 90-min exercise HA session was explored (five sessions in total, i.e., STHA). These researchers found that when this pre-heating strategy was adopted prior to STHA, comprehensive thermoregulatory, cardiovascular, and perceptual HA adaptations were induced in females, assumedly due to a measurably greater physiological strain in the 20-min sauna pre-heating, when compared to temperate exposure (Mee et al., 2018). Other notable female specific HA studies include that of Kirby and colleagues (2019), who found that typical HA adaptations and associated performance benefits were only observed in the final 5 days of a 9 day controlled hyperthermia HA protocol in recreationally active females, supporting the notion of longer temporal patterning in females.

Despite this notion of longer temporal patterning in females, five days of high-intensity exercise-based, controlled hyperthermia HA has been demonstrated to elicit favourable physiological and performance outcomes in international-level female soccer players (Pethick et al., 2018). Additionally, females performing 5 days of controlled hyperthermia STHA with permissive dehydration in a hot-humid (39.5 °C, 60% RH) environment led to significant physiological adaptations during an intermittent heat stress tolerance test in a compensable hot environment (31 °C, 50% RH) (Garrett et al., 2019). The increased humidity (and hence thermal stress) in the studies of Garrett et al. (2019) and Mee et al. (2018) induced physiological adaptations from STHA in females that were similar to those previously seen in males (Garrett et al., 2014; Garrett et al., 2011). In turn, these adaptations occurred more rapidly compared to similar controlled hyperthermia protocols in females in less humid environments (Kirby et al., 2019; Mee et al., 2015).

Taken together, the recent female specific HA protocols discussed above suggest that untrained or moderately trained athletes require a larger thermal impulse to induce HA adaptations than highly-trained individuals (Taylor, 2014; Wickham et al., 2021). This concept seems logical, as it has been previously suggested that trained athletes are inherently further along the HA adaptation spectrum, due to training-related sudomotor and cardiovascular adaptations (Gibson et al., 2019a; Taylor, 2014). Notably, the STHA protocols shown to be effective at inducing HA adaptations and performance benefits in females (Mee et al., 2018; Pethick et al., 2018), have involved (relatively) intensive and sustained HA sessions (e.g. five days of 90-min heat exposures, clamped at a T_c of 38.5 °C), such that the thermal impulse across these protocol is relatively high, compared to successful STHA studies in males (Tyler et al., 2016). As such, Wickham and colleagues (2021) recently suggested that the observed sex differences in temporal response to HA may be a product of differing thermal loads (combination of T_c, metabolic and environmental heat gain, and heat storage). These sex differences (described in Table 2-3) imply that females experience a lower thermal load compared to males during a typical HA session. For example, in controlled hyperthermia HA protocols the T_c is normally clamped to 38.5 °C, regardless of sex, meaning the absolute thermal stress to the body may not be equal between sexes (Wickham et al., 2021). An applied example of this phenomenon comes from the study described above by Mee et al. (2015), whereby male and female participants exercised at the same relative intensity (~ 65% $\dot{V}O_{2max}$). This protocol resulted in females performing significantly less total work per session than males during STHA (~ 413 vs. ~ 562 kJ) and MTHA (~ 487 vs. 653 kJ), which therefore generated lower metabolic heat production, and provided a smaller stimulus for sweating (Schwiening et al., 2011). Further supporting this theory is the fact that the workload performed by males in the STHA (~ 562 kJ) was comparable to the workload performed by females following MTHA (~ 487 kJ), emphasising that a threshold in thermal impulse may need to be attained to induce meaningful physiological HA adaptations (Mee et al., 2015; Wickham et al., 2021). As discussed above, this concept is supported by the subsequent research of Mee and colleagues (2018), whereby pre-loading exercise-based HA sessions with sauna exposures elicited STHA adaptations in females that were not present with a thermoneutral pre-load. Therefore, it seems that a significant factor in HA induction may be ensuring that a sufficient (and progressive) thermal impulse is provided on an individual basis, with one key differentiation being sex.

Table 2-3: Sex differences in the factors influencing the thermal load accrued during HA sessions.

Male		**Female**	
Physiological factor	***Heat factor***	***Physiological factor***	***Heat factor***
Increased body mass	Increased heat storage capacity	Body composition differences (reduced muscle mass, increased fat mass)	Decreased heat storage capacity
Increased absolute workload	Increased metabolic heat load	Increased surface area: volume	Increased heat loss (particularly in dry conditions)
Increased absolute $\dot{V}O_{2max}$		Menstrual cycle	Hormonal changes resulting in ΔT_c across cycle

2.8 Applied considerations for heat acclimation in an elite team sport context

As outlined in the sections above, repeated heat exposures can result in a plethora of physiological and perceptual improvements, acting to improve whole body thermotolerance and subsequent exercise performance (Sawka et al., 2011; Taylor, 2014; Tyler et al., 2016). Despite these clear advantages, the integration of HA prior to competition in hot conditions has been shown to be underutilised in athletes (Périard et al., 2017), possibly due to logistical/practical constraints, and/or a lack of knowledge regarding effective periodisation of HA into a pre-competition training program (Guy et al., 2015). Additionally, some practitioners hold the belief that athletes are safeguarded from heat stress due to their training status or prior training/competition in hot weather, despite a lack of evidence to support this (Corbett et al., 2018).

Although traditional HA studies were based on workplace, military, and endurance sport contexts, more recent research has examined possible HA protocols for team sports performance (Guy et al., 2015; Pethick et al., 2018; Pryor et al., 2019a; Sunderland et al., 2008). This shift in focus is most likely driven by the growing number of pinnacle events being scheduled in hot locations, such as the Tokyo 2020 Summer Olympic Games, and the 2022 Football World Cup in Qatar, along with evidence that heat is associated with a decrease in some determinants of match-play performance (Morris et al., 2000; Racinais et al., 2014; Sunderland et al., 2008). As per many disciplines, the differences between research and practical applications can be quite distinct. In this regard, the plethora of recent HA research is practically useful for prescribing HA strategies in some contexts, such as endurance or individual sports, however, the sustained nature of many of the interventions, non-elite populations, and inter-individual variability make the ecological validity difficult to interpret in an elite team-sport context (Casadio et al., 2017; Gibson et al., 2019a). Furthermore, in most team-sport pre-competition periods, competing training priorities and logistical/practical burdens prohibit such controlled, sustained, and high-intensity exercise-based HA sessions being included at such a time. While general recommendations on training and competing in the heat have been available for some time (Racinais et al., 2015), they provide limited practical information for athletes and coaches to integrate HA into training periodisation models (Casadio et al., 2017). Recently, Gibson and colleagues (2019a) endeavoured to alleviate this lack of applicability to athletes by providing practitioner guidelines, based on a review of heat alleviation strategies for athletic performance. While this was useful in many circumstances, the guidelines are based on very limited research in team (particularly elite) sport training programs, and thus interpretation and applicability within the current elite rugby sevens context is questionable.

Heat acclimation for team-based sports is complex for a variety of factors, including individual athlete differences, positional requirements, and concurrent team training schedules. As such, most HA protocols undertaken in a team sports context either consist of training camps or game simulations performed in hot conditions using short-term/high intensity HA protocols (Duvnjak-Zaknich et al., 2019; Pethick et al., 2018; Racinais et al., 2014; Sunderland et al., 2008). In general, these strategies have been shown to result in partial HA adaptations in moderate and well-trained male athletes, evident through reductions in heart rate and perceptions, along with increases in plasma volume and sweat rate (Gibson et al., 2019a). Similarly, in field-based team-sports, HA has also been shown to improve intermittent exercise capacity and tolerance to the heat (Duvnjak-Zaknich et al., 2019; Pethick et al., 2018), along with ~5% improvements in distance covered during tests of team sport skills in hot conditions (Racinais et al., 2014). While this emerging evidence suggests that HA has the potential to improve determinants of team sport performance in a hot environment, more evidence is required to optimise HA protocols in an elite context, with particular regard to integrating heat within the complexities of an elite athlete's training and competition schedule, especially if practical/logistical limitations preclude travel to a hot location pre-competition (Casadio et al., 2017).

Of the limited team-sport based HA interventions, only one has investigated the decay of adaptations, indicating that prolonged repeat-sprint performance in the heat is well-maintained over a subsequent two-week period, despite removal of any heat stimulus (Duvnjak-Zaknich et al., 2019). Even though this study was undertaken in moderately trained athletes, it is of interest to team-sport practitioners regarding the placement of HA into the macro- and meso-training periodisation (Gibson et al., 2019a). Although there is limited current evidence of adaptation retention in team-sport athletes, research supports the assertion that maintaining high (non-heat specific) physical activity levels post-HA, acts to prolong HA adaptations (Pryor et al., 2019a).

2.8.1 Heat response or heat stress testing

Heat response, or heat stress tests (HRT; HST) are traditionally used pre-and post HA to quantify the effectiveness of a HA protocol. Current guidelines recommend that HA protocols (and hence HRT) should be specific to the demands of an athlete's sport (Racinais et al., 2015). This specificity permits simple integration of heat stimulus into an existing training schedule, and allows athletes to experience heat stress in a situation that reflects their competitive environment, which may be useful for specific post-acclimation performance (Casadio et al., 2017; Racinais et al., 2015; Wingfield et al., 2016). Many HA protocols have been designed for endurance athletes, and reflected in the design of most HRTs among the literature (Tyler et al., 2016). In contrast, there are limited HRTs specific to team-sport contexts, particularly at an elite level (Garrett et al., 2019; Pethick et al., 2018). HRTs generally contain a sustained period of fixed-load work, followed by a component of maximal exertion or time to exhaustion (such as a time-trial), which provides a performance measure in the heat (Daanen et al., 2018). Ultimately, for many coaches and athletes, it is this improved performance during a standardised test that provides the most important evidence of HA adaptation (Pryor et al., 2019a). Hence, in a sporting context it is important to make the test as relevant to an athlete's sporting pursuit as possible, within the bounds of practical and logistical constraints.

For example, rugby sevens is characterised by repeated bouts of high-intensity running, frequent contacts, sprints, skill execution, and spatial awareness, played over two 7-min halves, with seven players per team (Henderson et al., 2018; Ross et al., 2015a). Players have been reported to cover a total of ~1500 m in one game, with ~250 m being above an arbitrarily assigned high-speed running threshold of 5.0 $m \cdot s^{-1}$, and maximal running velocities of 8.0 to 8.5 $m \cdot s^{-1}$ (Ross et al., 2015a). Previous attempts at simulating these match demands into a testing regime have been attempted: Douglas and co-authors (2016) investigated the parasympathetic reactivation on sympathetic drive during simulated rugby sevens whereby athletes completed two 7-min halves of repeated 30-m running sprints; and Furlan et al. (2016) assessed the ecological validity and reliability of a rugby sevens simulation protocol, whereby athletes undertook typical running and collision activities across two 7-min halves outdoors.

Although these previous simulations have ecological validity in terms of on-field running, within a full-time professional rugby sevens season, it is common practice to conserve running load for specific training. In this case, off-feet conditioning is often used to compliment running exercise in order to obtain/sustain cardiovascular and metabolic adaptations, without the mechanical load-bearing stress that running exerts (Hamlin et al., 2017; Wehbe et al., 2015). In turn, given the lack of control of outdoor environmental conditions, such protocols are not feasible to act as HRTs due to the necessity to monitor physiological responses and closely control the thermal impulse.

2.9 Measurement of body temperature variables

The measurement of core body temperature (T_c) is fundamental to assessing the outcomes of a HA protocol and can be used as a method of controlling the thermal stimulus during the a HA protocol itself as noted in Section 2.3.3 (Taylor et al., 2014). In turn, the measurement of skin temperature (T_{sk}) is used widely, including for evaluating aspects of thermal strain (e.g., sweating onset and sensitivity), estimating mean body temperature, and understanding aspects of sport performance (MacRae et al., 2018; Sawka et al., 2011). Furthermore, T_{sk} plays an important role in human heat exchange and the overall thermoregulatory response (Sawka et al., 1984) As such, the assessment of T_c and T_{sk} during exercise has been widely investigated among the literature, resulting in general agreement regarding the validity, reliability, and application of various thermal measurement apparatus. The standard method of T_c measurement in a laboratory setting seems to be via esophageal and/or rectal thermometry (Taylor et al., 2014), while hard-wired skin thermistors are traditionally recognised as the standard measure for T_{sk} (James et al., 2014). These methods provide excellent validity and reliability; however, the application of these gold-standard assessment methods are limited to a laboratory or clinical setting, due to the invasive, inconvenient, and sometimes expensive nature of implementation (Byrne & Lim, 2007).

Recently, wireless technologies to evaluate both T_c and T_{sk} in a practical sport setting have been developed. While such measurement apparatus allows for practitioners and researchers to assess these important thermoregulatory variables in the field, the validity and reliability of many devices and methods remain unclear and controversial (Bongers et al., 2018; Ganio et al., 2009a). During recent work in the field, ingestible telemetry pills have emerged as a favourable method of T_c assessment, with modern systems allowing for remote measurement of gastrointestinal temperature during practical and field settings (Ruddock et al., 2014; Taylor et al., 2019b). Currently there are numerous proprietary ingestible telemetry pill systems that can remotely assess T_c, with excellent validity, test-retest reliability, and inertia for each system when T_c is between 36 °C and 44 °C (Bongers et al., 2018). In addition, Bogerd and colleagues (2018) indicated that the ingestible telemetry pills react faster to body temperature changes compared to the rectal temperature probe, in particular during the rest period following exercise. Previous investigations had shown that ingestible telemetry pill systems can reflect both rectal and esophageal temperature reliably when changes in T_c are small and/or gradual (Easton et al., 2007). However, under higher rates of change (such as high-intensity exercise), temperatures obtained from both telemetry pills (and rectal thermometers) are slower to respond than esophageal temperature (Byrne & Lim, 2007), in some cases resulting in a deviation in gastrointestinal and rectal temperature by up to 1 °C at the end of a maximal exercise bout. This delay is likely triggered by a reduction in splanchnic blood flow during maximal-intensity exercise, and produces a peak temperature delay of 5 to 6 minutes, which is an important consideration for practitioners and researchers using such systems under high-intensity exercise conditions (Teunissen et al., 2012).

The cost-prohibitive and single-use nature of telemetry pill systems mean that in many cases they are impractical, particularly when continual assessment of T_c is needed in a group of athletes. In this regard, previous studies have investigated the suitability of tympanic membrane temperature (T_{Tymp}), as assessed via infrared thermometry, as an alternative to the invasive and/or expensive criterions (Huggins et al., 2012; Sato et al., 1996). T_{Tymp} assessment has been shown to be a convenient and reliable measurement method in clinical and resting settings (Easton et al., 2007; Gasim et al., 2013). However, the evidence supporting the reliable use of T_{Tymp} during exercise is equivocal. For example, investigations during exercise in the heat have shown T_{Tymp} to underestimate T_c by 0.9 to 1.1 °C (Easton et al., 2007; Huggins et al., 2012), leading to its validity often being questioned within exercise physiology and performance science contexts (Casa et al., 2007; Taylor et al., 2014). Conversely, Fogt and colleagues (2017) reported no difference in mean temperature between T_{Tymp} and telemetry pill measurements across 45-minutes of staged treadmill exercise in the heat, and Moran-Navarro et al. (2018) recently demonstrated improved agreement, whereby a tympanic thermometer registered a mean difference of 0.1 ± 1.9 °C (± 95% LoA) during exercise in the heat compared to an ingestible T_c pill.

An important consideration with auxiliary temperature measurement sites such as T_{Tymp} is inter-device and inter-measurer reliability (Taylor et al., 2014). Yeoh and colleagues (2017) revisited this problem, suggesting that greater agreement between T_c and T_{Tymp} can be obtained when the tympanic thermometer is correctly pointed at the tympanic membrane. As such, this leads to the notion that if using tympanic thermometry, the measurer should be familiar with the device and its utility, along with the each device being independently validated, given the discrepancies between devices seen in the literature (Fogt et al., 2017; Moran-Navarro et al., 2018; Yeoh et al., 2017).

In a similar manner to the assessment of T_c, laboratory-based, gold-standard measures of T_{sk} are impractical for use in the field and other applied settings. Unlike T_c measurements however, some universally used valid alternatives do exist (i.e., the iButton; Maxim Integrated Products Inc., California, USA) (van Marken Lichtenbelt et al., 2006). Since their inception in the early 2000s, iButtons have been proved to provide a valid and user-friendly alternative for human skin temperature measurement during laboratory and field investigations (Smith et al., 2010). This validity has been demonstrated in a controlled water bath setting, along with on human skin during exercise in the heat, with a typical error of <0.3 °C, and CV <1% when compared against wired thermistors (Smith et al., 2010). Despite the convenience of iButtons for measurements in novel environments, the lack of real-time data has prohibited their use in safety monitoring and research settings. As such, the use of recently developed telemetry thermistor systems for the measurement of T_{sk} (thermistors connected to a transmitter worn on the person) may offer the benefits of live data without the restrictions associated with wired thermistors (James et al., 2014). Furthermore, such systems have been demonstrated to provide a valid and reliable measure of T_{sk}, indicating that it is appropriate for use within environmental physiology research (James et al., 2014).

A further alternative for T_{sk} measurement is the use of portable infrared camera that detect infrared radiation emitted from the skin. This method has the advantage of being user friendly and convenient. Furthermore, it is not prone to measurement variation resultant from ambient temperature change or individual metabolic responses during exercise (Bach et al., 2015b; Moran & Mendal, 2002). However, the limitations of portable infrared cameras, such as the need for constant measurement angle and distance to reduce measurement error, leading to some uncertainty regarding its practicality in the field (James et al., 2014). In one laboratory-based study, Buono and colleagues (2007) indicated that T_{sk} measurements from infrared cameras demonstrated strong associations with wired thermistors at rest (r =0.95) and whilst walking in the heat (r = 0.98) (Buono et al., 2007); however, the validity of using this technology in the field is questionable given the need for a constant standardisation of the measurement angle and distance. Conversely, Fernandes and colleagues (2014) found significant mean bias between an infrared camera and criterion thermocouples at rest, and during exercise and recovery with differences ranging from 0.8 to 1.2 °C, concluding that there was a poor correlation and low reliability between the two measurement modalities. These data indicating low validity and reliability for T_{sk} measurement between portable infrared cameras and criterion measurements are not in uncommon. Bach and colleagues (2015b) reported significant mean bias (± LoA) at rest (0.8 ± 0.8 °C) and recovery (1.9 ± 1.9 °C), while James and colleagues (2014) demonstrated poor validity (mean bias = - 1.4 °C, typical error = 0.4 °C) and reliability (mean bias = - 0.7 °C, typical error = 0.5 °C) during exercise between the two measurement modalities.

Taken together, it seems that there are portable measurement tools available for the practitioner; however, these tools likely come with some form of caveat (e.g., low validity and reliability, prohibitive cost, set-up time, lack of live data) that may impact their application. With recent advances in technology, future research should endeavour to evaluate modern T_c and T_{sk} thermometry methods, such as modern derivatives of infrared thermometers.

2.10 Cooling strategies

Fundamentally, pre-, and per-cooling strategies reduce heat stress by increasing an individual's heat storage capacity. Besides HA (i.e. physiologically adapting to heat stress), the application of cooling strategies form one of the main interventions that can alleviate environmental heat stress (Racinais et al., 2015). These strategies can either be performed before (i.e., pre-cooling) or during (i.e., per-cooling) an athletic event, with the desired physiological alteration being a reduction in T_c, along with concurrent perceptual benefits (Bongers et al., 2017; Tyler et al., 2015). Pre-cooling aims to lower T_c and T_{skin} prior the onset of exercise, thereby (partially) negating the adverse effects of heat stress, and increasing the capacity for metabolic heat production and heat gain, thus enabling athletes to perform more work before a 'critical T_c' limit is reached (i.e. >40 °C; discussed below) (Bongers et al., 2017; Tyler et al., 2015). Per-cooling aims to mitigate the exercise-induced rise in T_c, thus delaying the onset of hyperthermia induced fatigue (Bongers et al., 2017). Per-cooling is often used as a complementary, or independent heat management strategy alongside pre-cooling and HA. Individually, cooling methods show some efficacy in improving performance in both endurance and intermittent sprint contexts (Tyler et al., 2015). However, the practicalities of optimal incorporation of pre- and per-cooling into athletic training and performance requires considerable thought, especially considering the positive effects of elevated muscle temperature on performance (Section 2.2.4).

In addition to the differences in timing of cooling strategies, cooling can be further differentiated into internal or external cooling. Pre-cooling methods can be separated into internal or external cooling techniques. Internal cooling techniques typically involves some form of ice ingestion (i.e., ice slurry ingestion, cold water ingestion) prior to, or during competition, while external cooling involves typically involves cold-water immersion (CWI), cold air exposure, partial body cooling using either cooling vests or ice packs. See Table 2-4 for an overview of different cooling techniques used for pre-, per-, and post-cooling.

Various mechanisms have been suggested to be responsible for the benefit of such cooling strategies. It has been demonstrated that a critical core temperature (e.g. ~40 °C) is associated with exercise termination, leading to the suggestion that a neural safeguard may act to terminate exercise if a critically high T_c is obtained (Bongers et al., 2017; Nybo et al., 2014). However, further analysis suggests that retaining a large core to skin temperature gradient may be more important to maintain exercise performance, rather than keeping T_c below the 'critical T_c' (Ely et al., 2009). In particular, the ability to sustain endurance exercise performance at a T_c above the critical T_c may be explained by the preservation of a (relatively) cool skin temperature, which ensures a sufficient core to skin temperature gradient, and thus the an increased capacity for heat loss (Cheuvront et al., 2010; Ely et al., 2009). Also, in a similar manner to those discussed above in Section 2.2, cooling reduces the stress on the cardiovascular and metabolic systems (Gonzalez-Alonso et al., 2008) as T_c reductions during exercise may increase the lactate threshold and prevent blood lactate accumulation (James et al., 2015). Furthermore, a lower T_c has been shown to reduce heart rate at a given workload (Olschewski & Brück, 1988), and to reduce the cutaneous circulation that inhibits cardiac filling (James et al., 2015). Taken together, the evidence presented across various recent reviews and meta-analysis suggest that a reduction in T_c prior to or during exercise may act to delay hyperthermia-induced fatigue, and thus be beneficial for exercise performance/capacity (Bongers et al., 2017; Douzi et al., 2019; Douzi et al., 2020; Périard et al., 2021; Ruddock et al., 2017; Tyler et al., 2015).

Table 2-4: Overview of different cooling techniques used for pre-, per-, and post-cooling.

Cooling Technique	Timing of cooling	Temperature of cooling	Advantages	Disadvantages/considerations
Cold-water immersion	Pre Post	10 – 25 °C	Large skin surface area coverage Direct contact with skin	Labour-intensive set up Difficult to use in field-settings
Ice slushy ingestion	Pre Per	~0 °C	Direct effect on T_c Easy to accomplish in field-settings	No direct impact on T_{skin} Requires adequate preparation facilities/resources
Ice vest application	Pre Post	< 0 °C	Covers a large component of the body High cooling efficacy/power	Heavy, can be logistically/practically challenging in field-settings
Cooling vest application	Pre Per	10 – 20 °C	Covers a large component of the body Light weight Easily applicable in field-settings	Low cooling efficacy/power
Cooling pack application	Pre Per	< 0 °C	Easily applicable in field-settings High cooling efficacy/power Adaptable for different circumstances	Movement restrictive Heavy, can be logistically/practically challenging in field-settings
Cooling garment application (towel, hat etc)	Pre Per	< 10 °C	Easily applicable in field-settings Adaptable for different circumstances	Low cooling efficacy/power
Wind and/ or water spray	Pre Per	< 15 °C	Can cover a large part of the body	Difficult to use in field-settings
Menthol ingestion and/ or application	Pre Per	Not applicable	Easy to accomplish in field-settings	Equivocal evidence for efficacy Best method of application unknown
Cryotherapy	Pre Per	< -100 °C	Covers a large component of the body	No contact with skin Expensive and unrealistic for most field settings

2.10.1 Pre-cooling

Numerous studies have assessed the benefits of pre-cooling in an athletic context, of these, many different methods have been identified to be beneficial to exercise performance in the heat. Pre-cooling methods can be separated into external [i.e., cold-water immersion (CWI), cold air exposure, partial body cooling using either cooling vests or ice packs] and internal cooling techniques (i.e. ice slurry ingestion, cold water ingestion, etc). Of these, the most common pre-cooling methods include CWI, ice slushy ingestion, and application of ice vests or ice packs, while a combination of methods has been suggested to be the most beneficial for subsequent exercise performance (Bongers et al., 2017).

Given that heat exchange relies upon thermal gradients and surface area for such gradients to act, CWI has the greatest potential to cool the body (Casa et al., 2015). With demonstrated relationships between pre-cooling volume (i.e. surface area) (Minett et al., 2011), duration (Minett et al., 2012), and exercise performance. As such, the performance benefits of CWI are well-established for both intermittent-sprint and prolonged endurance exercise (Bongers et al., 2017; Duffield et al., 2010). Despite these well-established benefits, CWI pre-cooling still requires significant logistical challenges to be overcome for application in a field setting (Gibson et al., 2019a). Accordingly, more feasible pre-cooling combinations (e.g., cold garments and partial body CWI) may be preferable for athletes and practitioners (James et al., 2015; Minett et al., 2011). As with whole body CWI, the effectiveness of these other pre-cooling approaches is determined by a combination of the temperature gradient, skin surface area coverage, and cooling capacity (Bongers et al., 2017).

Although pre-cooling using CWI has the potential to enhance fatigue resistance (Beaven et al., 2018), it also has the potential to negatively impact upon the ability of the muscle to produce force rapidly, particularly at the onset of an exercise event. As such, some practitioners and athletes (particularly those involved in shorter duration, high intensity pursuits) may not favour such methods. In this regard, internal pre-cooling using cold water or ice slushy (a.k.a. ice slurry) ingestion avoids direct musculature cooling, and has been demonstrated to have positive effects on exercise performance in a variety of endurance based-contexts (Burdon et al., 2010; Siegel et al., 2010; Stevens et al., 2013; Yeo et al., 2012). For example when consuming a 7.5 g/kg ice slurry beverage for pre-cooling, Siegel and colleagues (Siegel et al., 2012) observed reductions in T_c comparable to those seen with CWI (~0.5 °C), along with improved exercise time to exhaustion (Siegel et al., 2010).

Irrespective of this evidence of enhanced endurance performance resulting from ice slushy pre-cooling, Gerrett and colleagues (2017) recently demonstrated that ice slushy ingestion may not have the same benefits for self-paced intermittent exercise in the heat. The authors indicated that despite lowering T_c and reducing thermal sensation in comparison to a control beverage, there were no clear performance benefits in such circumstances. These findings have been corroborated by Thomas and colleagues (2019) who found that independently or simultaneously lowering T_c and T_{skin} (using ice slurry and cooling garments) prior to self-paced intermittent exercise did not improve sprint, or submaximal running performance. Despite these results, the nature of team sport (such as rugby sevens) is that opposition play, and thus determinates of game outcomes are variable from game to game (Henderson et al., 2018; Ross et al., 2015d). As such, even though performance benefits of ice slushy pre-cooling during self-paced intermittent exercise are not obvious in a laboratory environment, demonstrated improvements in thermal perception may relate to behavioural changes in an applied field setting, which have the potential to impact on real-life performances (Schlader et al., 2011a).

In an applied team-sport context, recent research has indicated that the application of a phase-change cooling vest (i.e. an ice vest) prior to and during a match specific rugby sevens warm-up can elicit favourable alterations in T_c and perceptual responses, without compromising warm-up performance metrics, in both elite male (Taylor et al., 2019a) and elite female populations (Henderson et al., 2021). Specifically, in the study by Taylor and colleagues (2019a), athletes wearing an ice vest exhibited a smaller increase in T_c across the warm-up period compared to wearing no vest (1.3 ± 0.1°C vs. 2.0 ± 0.2 °C respectively; $d = -1.54 \pm 0.62$). Athletes wearing an ice vest also demonstrated a smaller increase in thermal sensation and thermal comfort pre- to post-warm-up with a lower RPE post-warm-up compared to those wearing no vest. Moreover, there were no detrimental effects revealed in countermovement jump or GPS indices measured post warm-up between groups, further indicating the application of ice vests in this context.

While such pre-cooling methods seem efficacious when used in isolation, a mixed-methods pre-cooling approach may be advantageous, particularly if vigorous cooling methods are not feasible (Gibson et al., 2019a). For example, a study by Aldous and colleagues (2018) indicated that 30-min of mixed methods pre-match cooling (ice slurry ingestion and ice packs) improved simulated soccer performance in the heat. Interestingly, even though the authors investigated the impact of concurrent half-time cooling, they found that no half-time cooling strategy when combined with pre-match cooling improved simulated soccer performance in the heat (Aldous et al., 2018). These findings suggest that future research should attempt to apply well defined pre-match cooling methods in a real-life setting, while in turn, laboratory-based research should identify aggressive cooling strategies that are compatible with a sports-specific half-time break, in order to augment second half performance.

2.10.2 Per-cooling

While pre-cooling strategies have more flexibility in terms of their timing and application, per-cooling strategies are largely determined by the structure of an athletic event, along with athlete acceptability (Bongers et al., 2017; Gibson et al., 2019a); see Table 2-4. In terms of efficacy of per-cooling systems, Bongers and colleagues (2017) indicated performance improvements resulting from the use of ice vests (~11%) and ice slushy ingestion (~6%). Further evidence of the benefit of using a cooling vest during half-time of a simulated intermittent team sport was provided by Chaen and colleagues (2019), whereby significant improvements in intermittent exercise performance in the heat, along with decreased mean T_{skin} and improved subjective responses were described. Recently there has been interest in the use of menthol as a per-cooling method, either as a beverage, mouth rinse, or topical application (Best et al., 2018). Currently, however, the evidence for the efficacy of menthol is equivocal and situation dependent. For example, menthol mouth-rinsing may elicit an ergogenic effect during self-paced endurance exercise in untrained individuals (Stevens & Best, 2017), however, no positive effect were observed in intermittent sprint (i.e. team sport) exercise (Gibson et al., 2019b).

Taken together, most per-cooling strategies are effective at improving thermotolerance and subsequent exercise performance in hot and temperate conditions, while the degree of effectiveness is dependent on the volume of cooling and the extent of the thermal strain experienced (Douzi et al., 2020; Tyler et al., 2015). It must be noted that cooling strategy research in an applied field is scarce, hence practitioners should trial strategies for application to their program, as well as allowing for individual preferences.

2.11 Literature review summary

There is a plethora of research investigating the effects of heat stress and HA in untrained and recreational, predominantly endurance athletes. Subsequently, a range of physiological mechanisms and adaptations associated with HA has been well described in these populations. Although there is a small number of research studies describing the efficacy of HA to induce performance enhancing adaptations in highly-trained athletes, this is predominantly limited to endurance athletes, with a scarcity of HA research within the microcosm of elite team-sport. Heat acclimation is widely recognised as the most important intervention to minimise heat-induced physiological strain, lower the incidence of heat-illness, and improve athletic performance and recovery in the heat. However, a major concern for practitioners is that existing HA protocols, traditionally used in endurance or individual athletes, are impractical to incorporate into a pre-competition training period due to increased training stress impacting the quality of other training modes that are deemed more important (such as strength, skill, and field training). Therefore, an emerging theme is the development and implementation of HA protocols that can synchronise with the day-to-day training of elite teams. This requirement presents multiple challenges, including the lack of access to facilities to enable an effective thermal impulse (e.g., a hot outdoor environment or environmental chamber), or the inability to run an acclimation intervention to the squad concurrently. These reasons are in part why the emergence of passive HA strategies have been investigated (such as sauna bathing, hot water immersion). Whilst these strategies alone have shown some efficacy to induce HA in athletes and subsequently improve exercise performance, they have not been used in combination with traditional exercise heat exposures, or within an elite, intermittent team sport context. Furthermore, the retention of adaptations following the removal of heat acclimation stimulus has not been fully elucidated, particularly when considering the large variability of initial thermal stimuli amongst the literature.

While HA remains the most important intervention to minimise exercise heat stress, the application of appropriate cooling strategies can also act to further augment this on the day of competition. The efficacy of pre- and per-cooling strategies have been well described in endurance and non-elite team sports, however, due to the relatively short and high intensity nature of team sports such as rugby sevens, it is unclear whether traditionally used cooling strategies are efficacious in such a context.

2.12 Research questions

Research question one

Are minimally invasive, practical devices designed to measure T_c and T_{skin} pre-, during-, and post-exercise in the heat valid and reliable alternatives for laboratory-based, invasive, and expensive measures of T_c and T_{skin}?

Research question two

What are the T_c characteristics/profiles during an international rugby sevens tournament performed in hot and humid conditions; and what physiological and/or performance characteristics mediate such T_c profiles?

Research question three

Can a specifically designed off-feet (cycling) heat response test provide a similar physiological stimulus as a running test, while also being specific to the physiological demands of elite rugby sevens? Furthermore, what are the physiological and performance responses of elite rugby sevens players between a ambient environment (20 °C, 50% RH) and the thermally challenging conditions expected at the Tokyo 2020 Olympics (35 °C, 80% RH)?

Research question four

What is the effectiveness of two-weeks of mixed-methods heat acclimation, integrated within an elite male rugby sevens teams training program? Furthermore, are any resulting physiological, perceptual and performance changes retained after 15 days of normal training, without any further heat stimulus?

Research question five

What are the physiological, perceptual, and performance adaptations resulting from a 10-day (primarily) passive heat acclimation protocol integrated into an elite female team-sport training program? Furthermore, are any resulting adaptations be retained after 15 days without any further heat stimulus?

Research question six

What is the effectiveness of the combined use of ice slurry ingestion and the application of ice towels to the head and neck before and during a rugby sevens specific heat response test in a controlled environment?

Chapter Three Validity of a tympanic thermometer and thermal imaging camera for measuring core and skin temperature during exercise in the heat

Fenemor, S. P., Gill, N. D., Sims, S. T., Beaven, C. M., & Driller, M. W. (2020). Validity of a tympanic thermometer and thermal imaging camera for measuring core and skin temperature during exercise in the heat. *Measurement in Physical Education and Exercise Science, 24*(1), 49-55. https://doi.org/10.1080/1091367X.2019.1667361

Prelude

As highlighted in Chapter 2.9, portable measurement tools are available for the practitioner; however, these tools likely come with some form of caveat (e.g., low validity and/or reliability) that may impact their application. Therefore, in the context of the current thesis, validation of temperature measurement tools was an important consideration.

3.1 Abstract

This study compared criterion to minimally invasive, practical measures of core (T_c) and skin (T_{sk}) temperature during 30-minutes of moderate-intensity cycle exercise in a heat chamber (35 °C, 60% RH). T_c was monitored using a core temperature pill ($T_{c(Pill)}$) and tympanic thermometer ($T_{c(Tymp)}$) during rest, exercise, and recovery in 15 participants. T_{sk} was monitored using hard-wired skin thermistors attached to a data logger ($T_{sk(T)}$) and a thermal imaging camera ($T_{sk(IR)}$) in 11 participants. T_c measurement resulted in no significant difference ($p > 0.05$), a mean bias of 0.1 °C, coefficient of variation (CV%) of 1.0%, and correlation of $r = 0.74$ between devices. T_{sk} measurement resulted in a significant difference ($p = 0.01$), a mean bias of 0.6 °C, CV% of 2.3%, and correlation of $r = 0.61$ between devices. $T_{c(Tymp)}$ demonstrated acceptable agreement with $T_{c(Pill)}$, however, caution is advised when using $T_{sk(IR)}$ to give accurate measures of T_{sk} during exercise.

3.2 Introduction

The assessment of core (T_c) and skin (T_{sk}) temperatures during exercise has been widely investigated, resulting in general agreement regarding the use and application of thermal measurement apparatus. Most commonly, esophageal and rectal thermistors are used as standard measures for T_c (Casa et al., 2007), whereas thermistors hard-wired to multiple skin sites are used to assess T_{sk} (Bach et al., 2015a; Moran & Mendal, 2002). The application of many of these 'gold standard' assessment methods are often limited to a laboratory or clinical setting, due to the invasive, inconvenient, and sometimes expensive nature of implementation. Developments in wireless technology to evaluate both T_c and T_{sk} in a practical sport setting may allow for practitioners and researchers to assess these important physiological factors in the field. Furthermore, given the increasing attention regarding thermal strain experienced by athletes competing in the heat, such as the conditions expected at the upcoming Tokyo 2020 Olympics, valid tools for evaluating both T_c and T_{sk} in these environments are required (Gerrett et al., 2019a).

Over the past two decades, ingestible telemetry pills have emerged as a favourable method of T_c assessment, with modern systems allowing for remote measurement of gastrointestinal temperature during practical and field settings (Ruddock et al., 2014; Taylor et al., 2014). These devices have been shown to reflect both rectal and esophageal temperature reliably when changes in core temperature are small and/or gradual (Easton et al., 2007). Under higher rates of change, it has been shown that temperatures obtained from both rectal thermometers and telemetry pills are slower to respond than esophageal temperature (Byrne & Lim, 2007). This delay can result in a deviation in gastrointestinal and rectal temperature from that of esophageal by up to 1 °C at the end of a maximal exercise bout, triggered by a reduction in splanchnic blood flow during maximal intensity exercise causing a peak temperature delay by 5-6 min (Teunissen et al., 2012). Telemetry pill systems are single-use and expensive, hence, can be considered impractical when continual assessment of T_c is needed in a group of athletes.

Previous studies have investigated the suitability of tympanic membrane temperature, as assessed via infrared thermometry, as an alternative to the invasive and/ or expensive criterions (Huggins et al., 2012; Sato et al., 1996). Tympanic temperature assessment is a convenient measurement method in clinical settings (Gasim et al., 2013), however, has been shown to underestimate T_c by 0.9 – 1.1 °C during exercise (Easton et al., 2007; Huggins et al., 2012), leading to its validity often being questioned within exercise physiology and performance science contexts (Casa et al., 2007; Taylor et al., 2014). Yeoh et al. (2017) revisited this problem, suggesting that greater agreement between T_c and tympanic temperatures can be obtained when the tympanic thermometer is correctly pointed at the tympanic membrane. Improved agreement was recently demonstrated, whereby a tympanic thermometer registered a mean difference of 0.1 ± 1.9 °C (± 95% limits of agreement; LoA) during exercise in the heat compared to an ingestible T_c pill (Morán-Navarro et al., 2018).

Comparable to the assessment of T_c, laboratory-based measures of T_{sk} are impractical for use in the field and other practically applied settings. It has been suggested that infrared radiation emitted from the skin (as assessed using a portable infrared camera) may be suitable for T_{sk} measurement, as it is not susceptible to measurement variation based on ambient temperatures or individual metabolic response during exercise (Bach et al., 2015b; Moran & Mendal, 2002). This infrared method is not without limitations; namely, measurement error can be introduced if constant measurement angle and distance is not maintained, leading to some uncertainty regarding its practicality in the field (James et al., 2014). Currently, the evidence is equivocal, with skin temperature measurements from infrared cameras demonstrating strong associations with wired thermistors at rest (r =0.95) and whilst walking in the heat (r = 0.98) (Buono et al., 2007); however, the validity of using this technology in the field is questionable.

Fernandes et al. (2014) found that mean bias between an infrared camera and thermocouples was significant during rest, exercise and recovery with differences ranging from 0.8-1.2 °C; concluding that there was a poor correlation and low reliability between the two measurement modalities. These poor results have been supported by other studies, with Bach et al. (2015b) reporting significant mean bias (± LoA) at rest (0.8 ± 0.8 °C) and recovery (1.9 ± 1.9 °C), and James et al. (2014) reporting poor validity (mean bias = - 1.4 °C, typical error = 0.4 °C) and reliability (mean bias = - 0.7 °C, typical error = 0.5 °C) during exercise.

Technological advances in the design and specificity of tympanic membrane thermometers and infrared cameras have the potential to limit the bias between laboratory based devices and in field, practical temperature measurement (Morán-Navarro et al., 2018). Hence, the purpose of the current study was to a compare laboratory based invasive measures of T_c (BodyCap; ingestible telemetry pill) and T_{sk} (hard-wired skin thermistors) with minimally invasive, practical devices designed to measure T_c (Braun ThermoScan® 7; tympanic membrane thermometer) and skin temperature (ICI ToughCam EL Scientific; handheld infrared imager) pre, during, and post exercise in the heat.

3.3 Materials and methods

3.3.1 Participants

Part one of the study involved 15 healthy, recreational athletes (9 male/6 female, age: 28 ± 7 years: body mass: 79.6 ± 13.9 kg) and part two included 11 recreational athletes (5 male/6 female, age: 27 ± 6 years; body mass: 75.3 ± 12.6 kg). All participants provided informed consent prior to testing and ethical approval for the study was obtained through the institution's Human Research Ethics Committee.

3.3.2 Study design

All participants for parts one and two of the study were required to attend the laboratory for a single testing session, however the analysis was divided into two parts; part one to assess core temperature (T_c) and part two to assess skin temperature (T_{sk}). The experimental session involved 30-minutes of exercise performed on a cycle ergometer (WattBike Ltd, Nottingham, UK) in an environmental chamber set at 35 °C and 60% relative humidity, representing an environment expected at the Tokyo 2020 Olympics, as described by Gerrett et al. (2019a). Participants were instructed to cycle for 30 min with a self-selected power output of between 1.5 – 2.0 Watts·kg.$^{-1}$ of body mass. Measurements of T_c and T_{sk} were taken at -5, 0, 10, 20, and 30 minutes before and during exercise, and 10 minutes post-exercise.

3.3.3 Core temperature (T_c)

Table 3-1 shows detailed specifications for the four thermometers used in the current study. The criterion measure of T_c was made using an ingestible telemetry pill and associated monitor ($T_{c(Pill)}$; e-Celcius™ BodyCap, Caen, France). An infrared tympanic membrane thermometer ($T_{c(Tymp)}$; Braun ThermoScan® 7 IRT6520, Braun GmbH, Kronberg, Germany) was validated against the telemetry pill. Participants were required to ingest the pill five hours prior to the start of the testing session. During the five hours between ingesting the pill and the commencement of the testing session, participants were asked to refrain from eating, however, drinking of water was permitted ad libitum during this time. No fluid was consumed during any of the testing phases (pre, during, post-exercise).

All measurements of tympanic temperature were made in duplicate in the left ear, with the mean of the two readings being used for comparison to $T_{c(pill)}$ in the final analysis.

3.3.4 Skin temperature (T_{sk})

The criterion measure of T_{sk} comprised of four hard-wired skin thermistors ($T_{sk(T)}$; Grant Type-U, Grant Instruments, Cambridge, UK) connected to a datalogger (Grant Squirrel 2020 series, Grant Instruments, Cambridge, UK). The surface of the mid-belly of the pectoralis major, anterior forearm, rectus femoris and gastrocnemius on the left of the body was cleaned with alcohol and allowed to dry before the thermistors were attached to the same site and affixed with a breathable polyester dressing (Fixomull® Stretch, BSN Medical, Stockholm, Sweden). Measures obtained from the hard-wired skin thermistors were compared to a handheld infrared thermal imaging camera ($T_{sk(IR)}$; ICI ToughCam EL Scientific Infrared Imager).

All thermal camera measurements were taken handheld, at ~1 m, with the camera at 90° to the relevant site as per the manufacturer's instructions. $T_{sk(IR)}$ measurements were taken 1 cm above the edge of the affixing dressing using the spot analysis function, assisted by the cameras laser pointer. In accordance with previous research, a constant skin emissivity for the infrared camera was set to 0.98 (Steketee, 1973), and a weighted measure of mean T_{sk} was completed using the derivative calculation as described by Ramanathan (1964). Four participants were missing skin temperature data at both 0 min and 10 min post-exercise.

3.3.5 Statistical analysis

In the current study, T_c and T_{sk} measurements were analysed separately. For T_c, a two-way repeated measures ANOVA (device * time) was conducted to test mean differences between $T_{c(pill)}$ and $T_{c(Tymp)}$. For $T_{sk,}$ due to some missing data (four points before and after exercise, respectively), a mixed-effects model was fitted using the restricted maximal likelihood approach to test mean differences between $T_{sk(T)}$ and $T_{sk(IR)}$. Sphericity was not assumed, whereby the Greenhouse-Geisser correction was used if this was violated. Normality was assessed using descriptive methods (distribution plots). Paired-sample post-hoc analysis using Šidák correction for multiple comparison was used to identify significant differences between devices. Statistical significance was set at $p \leq 0.05$.

Inter-device agreements ($T_{c(pill)}$ vs. $T_{c(Tymp)}$ and $T_{sk(T)}$ vs. $T_{sk(IR)}$) were examined using Pearson's correlation coefficients (r) with 95% confidence intervals (95% CI) and interpreted as 0.90–1.00 = *very high* correlation, 0.70–0.89 = *high* correlation, 0.50–0.69 = *moderate* correlation, 0.26–0.49 = *low* correlation and 0.00–0.25 = *little, if any* correlation (Munro, 2005). Bland-Altman analyses was also performed to describe inter-device agreement, with acceptable limits of agreements defined based on results from previous investigations (Bach et al., 2015b) and interpreted as acceptable (bias < 0.3 °C), inadvisable (0.3 °C < bias < 0.5 °C) and unacceptable (bias > 0.5 °C). Between-device typical error of estimates (TEE) was determined using a customised Excel® spreadsheet (Hopkins, 2010) and are presented as a coefficient of variation percentage (CV%) and as absolute values. Simple group statistics are shown as means ± standard deviations unless stated otherwise. ANOVA, mixed effect, and Bland-Altman calculations were made using GraphPad Prism 8.0 (GraphPad Software, Inc., CA, USA).

Table 3-1: Thermometer Specifications

	Core Temperature		Skin Temperature	
	Ingestible Telemetry Pill	Tympanic Thermometer	Thermistor (Data Logger)	Infrared Camera
Technology:	Thermistor	Infrared	Thermistor	Infrared
Operation:	Wireless	Contact	Contact	Handheld
Application:	Gastrointestinal	Eardrum	Skin	Wireless
Brand:	e-Celcius™, Caen, France	Braun GmbH, Kronberg, Germany	Grant Instruments, Cambridge, UK	Infrared Cameras Incorporated, Texas, USA
Model:	BodyCap	ThermoScan® 7 (IRT 6520)	EU-UU-VL5-0 (SQ2020)	ToughCam EL Scientific
Measuring range:	25 to 45 °C	34.0 to 42.2°C	-50 to 150 °C	-20 to 350 °C
Operating ambient:	-	10 to 40°C	-50 to 150 °C	-15 to 50 °C
Operating humidity:	-	10 to 95% RH	Not specified	10 to 95% RH
Accuracy:	± 0.2 °C	35 to 42 ± 0.2°C Outside range ± 0.3°C	± 0.1 °C (at 0 to 70 °C)	± 2 °C or ± 2% of reading (whichever is greater)

RH = Relative Humidity

3.4 Results

ANOVA generated no significant difference between devices for T_c measures ($F_{1, 26} = 1.4$; $p = 0.26$). There were significant differences for measurement time for the T_c ($F_{3, 90} = 28.9$; $p < 0.001$). Overall, T_c measurement resulted in a mean bias (± 95% CI) of -0.1 (± 0.1 °C) between devices, with a TEE of 0.4 (± 0.1 °C), a CV% of 1.0 (± 0.1%) and a correlation of $r = 0.74$, with $T_{c(Tymp)}$ reading slightly lower temperatures than $T_{c(Pill)}$.

Mixed effects analysis generated a significant difference between devices ($F_{1,20} = 7.80$; $p = 0.01$) and time ($F_{3,39} = 12.78$; $p < 0.01$) for T_{sk}. Weighted mean T_{sk} assessment resulted in a mean bias of 0.6 (± 0.2 °C) between devices, with a TEE of 0.7 (± 0.2 °C), a CV% of 2.3 (± 0.4%) and a correlation of $r = 0.61$, with $T_{sk(IR)}$ reading higher temperatures across all time points; all values are shown ± 95% confidence limits.

Comparisons and validity analysis between devices showing temperature means, bias, correlations, TEE, and CV are shown in Table 3-2 (T_c) and Table 3-3 (T_{sk}). Bland-Altman plots showing mean bias between devices are presented in Figure 3-1 ($T_{c(pill)}$ vs. $T_{c(Tymp)}$) and Figure 3-2 (T_{sk} vs. $T_{sk(IR)}$).

Table 3-2: Mean ± SD values for core temperature (T_c) between a core temperature pill ($T_{c(Pill)}$) and tympanic thermometer ($T_{c(Tymp)}$) at rest, exercise, and recovery. Comparisons between devices are reported using mean bias, Pearson correlations (*r*), typical error of estimates (TEE) and coefficient of variation percentage (CV%) with 95% confidence intervals.

	$T_{c(Pill)}$ (°C)	$T_{c(Tymp)}$ (°C)	Mean bias (°C)	Pearson's *r*	TEE (°C)	CV%
5 minutes pre	37.1 ± 0.5	37.0 ± 0.5	-0.1 (-0.4 – 0.2)	0.58 (0.41 – 0.95)	0.4 (0.3 – 0.7)	1.2 (0.8 – 1.9)
0 minutes	37.3 ± 0.5	37.2 ± 0.5	-0.1 (-0.3 – 0.1)	0.79 (0.44 – 0.93)	0.3 (0.2 – 0.5)	0.9 (0.6 – 1.4)
10 minutes	37.6 ± 0.4	37.5 ± 0.4	-0.1 (-0.3 – 0.1)	0.62 (0.14 – 0.87)	0.3 (0.2 – 0.5)	0.8 (0.6 – 1.4)
20 minutes	37.9 ± 0.4	37.9 ± 0.3	-0.1 (-0.2 – 0.1)	0.78 (0.43 – 0.93)	0.2 (0.2 – 0.4)	0.6 (0.4 – 1.0)
30 minutes	38.1 ± 0.3	38.0 ± 0.3	-0.1 (-0.2 – 0.1)	0.74 (0.35 – 0.91)	0.2 (0.2 – 0.4)	0.6 (0.5 – 1.0)
10 minutes post	37.9 ± 0.5	37.7 ± 0.3	-0.2 (-0.5 – 0.1)	0.34 (-0.23 – 0.74)	0.5 (0.4 – 0.9)	1.4 (1.0 – 2.4)
Overall	**37.7 ± 0.5**	**37.5 ± 0.5**	**-0.1 (-0.2 – 0.0)**	**0.74 (0.62 – 0.82)**	**0.4 (0.3 -0.4)**	**1.0 (0.9 – 1.2)**

Table 3-3: Weighted mean (± SD) values for skin temperature (T_{sk}) between the hard-wired skin thermistors ($T_{sk(T)}$) and the infrared camera ($T_{sk(IR)}$) at $_{)}$) at rest and exercise. Comparisons between devices are reported using mean bias, Pearson correlations (*r*), typical error of estimates (TEE) and coefficient of variation percentage (CV%) with 95% confidence intervals.

	($T_{sk(T)}$) (°C)	**($T_{sk(IR)}$) (°C)**	**Mean bias (°C)**	**Pearson's *r***	**TEE (°C)**	**CV%**
0 min	33.2 ± 0.6	34.1 ± 1.1	0.9 (0.5 – 1.3)	0.89 (0.61 – 0.97)	0.3 (0.2 – 0.6)	1.0 (0.7 – 1.7)
10 min	34.5 ± 1.0	35.0 ± 0.4	0.5 (-0.1 – 1.1)	0.56 (-0.06 – 0.87)	0.9 (0.6 – 1.6)	2.5 (1.7 – 4.6)
20 min	34.9 ± 1.0	35.2 ± 0.4	0.3 (-0.3 – 0.9)	0.25 (-0.41 – 0.74)	1.0 (0.7 – 1.8)	2.8 (1.9 – 5.3)
30 min	34.9 ± 1.0	35.2 ± 0.7	0.2 (-0.4 – 0.9)	0.32 (-0.34 – 0.77)	1.0 (0.7 – 1.8)	2.9 (2.0 – 5.3)
Overall	**34.2 ± 1.0**	**34.8 ± 0.7**	**0.6 (0.4 – 0.8)**	**0.61 (0.41 – 0.75)**	**0.7 (0.6 – 0.9)**	**2.3 (1.9 – 2.8)**

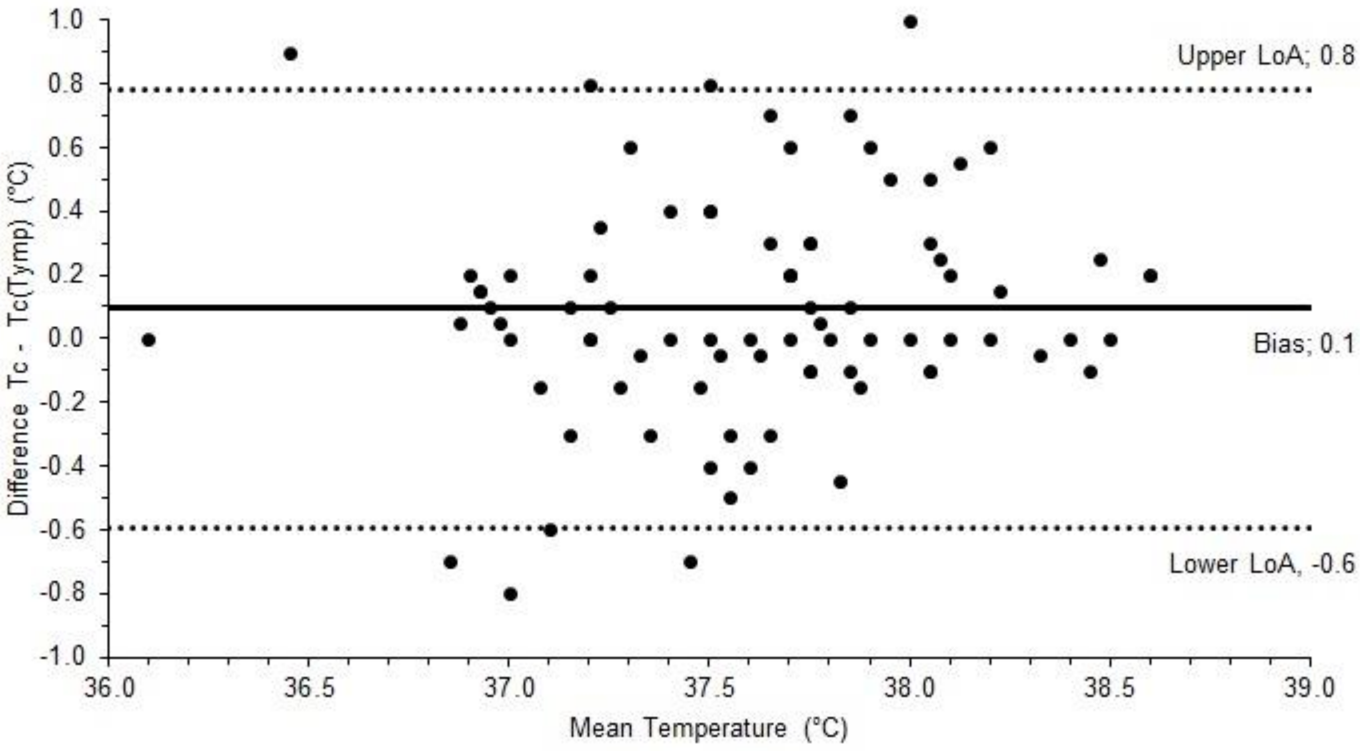


Figure 3-1: Bland–Altman plot indicating the mean bias (solid line) and 95% limits of agreement (dotted lines) in temperature between the ingestible telemetry pill (T_c) minus a tympanic thermometer $T_{c(Tymp)}$ before, during, and after exercise in hot (30 °C) and humid (60% relative humidity) conditions.

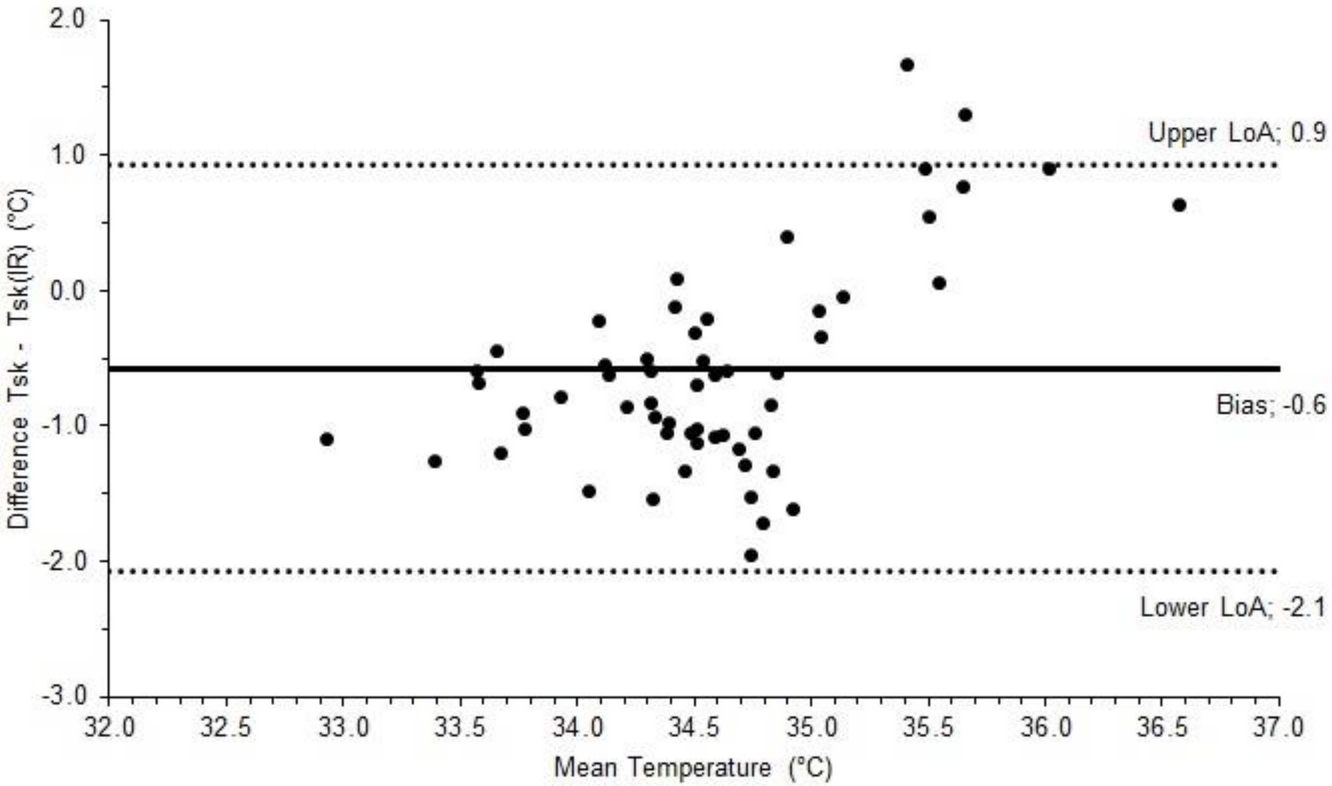


Figure 3-2: Bland–Altman plot indicating the mean bias (solid line) and 95% limits of agreement (dotted lines) in temperature hardwired skin thermistors (T_{sk}) minus a handheld thermal imaging camera ($T_{sk(IR)}$) before, during, and after exercise in hot (30 °C) and humid (60% relative humidity) conditions.

3.5 Discussion

The current study assessed the criterion validity of two minimally invasive practical measures of T_c and T_{sk}, compared with established measures during exercise in hot and humid conditions. Overall, T_c measurement resulted in an acceptable mean bias of 0.1 °C between devices, the correlation between $T_{c(Pill)}$ and $T_{c(Tymp)}$ was *moderate – high* (r = 0.62 – 0.78) at all exercise timepoints, however, *moderate* (r = 0.58) and *low* (r = 0.34) correlations were shown before and after exercise, with $T_{c(Tymp)}$ reading slightly lower temperatures than $T_{c(Pill)}$ at all timepoints. Weighted mean T_{sk} assessment resulted in an unacceptable mean bias of 0.6 °C between devices, the correlation between mean $T_{sk(T)}$ and mean $T_{sk(IR)}$ was *moderate* (r = 0.61), with $T_{sk(IR)}$ reading higher temperatures across all timepoints.

These results support those of Morán-Navarro et al. (2018), who recently showed that a tympanic thermometer (Braun ThermoScan® 7; the same model as used in the current study) registered similar temperatures to a telemetry pill system (CorTemp® system; HQ Inc., Florida, USA), with variations of just ~ 0.1 °C at rest and during exercise in the heat. Interestingly, those authors also reported significantly colder tympanic temperatures during recovery (mean difference between devices = 0.7 °C; p < 0.001), which is again similar to the findings of the current study. The telemetry pill system used by Morán-Navarro et al. (2018) has been shown to have a high prevalence of outliers (4.0%), leading to high systematic bias, compared to the e-Celcius® system used in the current study (limits of agreement = ~2.3 °C vs ~0.1 °C, respectively) (Bongers et al., 2018).

For a practitioner, these findings indicate that a tympanic thermometer may provide a valid assessment of T_c during exercise. However, caution should be taken if using such devices for monitoring during a recovery period due to the tendency for $T_{c(Tymp)}$ to underestimate that of $T_{c(Pill)}$. This underestimation has been noted in other investigations (Ganio et al., 2009b;

Huggins et al., 2012; Morán-Navarro et al., 2018), with a suggested mechanism being preferential brain cooling, resulting from forced vascular convection and conductive cooling (Cabanac & Caputa, 1979; Cabanac et al., 1987). Together, these results have a practical relevance given the direct relationship between tympanic and brain temperatures (Mariak et al., 1994). However, the underestimation of $T_{c(Tymp)}$ to that of $T_{c(Pill)}$ could equally be due to thermometers detecting auditory canal, rather than tympanic membrane temperature (Huggins et al., 2012).

With the exception of the study by James et al. (2014), the majority of previous research assessing the validity of thermal imaging cameras vs. criterion measures has implemented measurement techniques that are not feasible in a practical/field setting (specifically, a thermal camera mounted on a tripod, ensuring constant distance and angle from the measurement sites). Although some findings utilizing these techniques were encouraging, (r = 0.98 during exercise; bias not reported) (Buono et al., 2007), others have large mean bias (0.8 – 1.9 °C) between the two measurement modalities (Bach et al., 2015b; Fernandes et al., 2014). Regardless, this controlled approach does not allow a practitioner to assess athletes in real-time, hence is of little practical importance. The current study compared the live-view function on a handheld thermal imaging camera to hard-wired skin thermistors, supporting earlier findings by James et al. (2014), showing *low – moderate* correlations and unacceptable mean bias between devices for mean T_{sk} assessment during exercise, suggesting that infrared thermal imaging cameras may be of little practical use for live monitoring during exercise.

Although participants were stationary during the measurement periods, the angle and distance at which the infrared measurements were taken was not fixed in the current study, which may have increased measurement error (Hershler et al., 1992). Additionally, although sites for $T_{sk(T)}$ and $T_{sk(IR)}$ were in close proximity, skin preparation and attachment of the thermistors may have contributed toward the discrepancy seen in the current findings, as interindividual variation of vascularization can result in measurement error when taking readings from a single spot on an image or from attached thermistors (Chudecka & Lubkowska, 2012), and thermistors were attached using a breathable polyester dressing, which may overestimate relative to uncovered skin (Tyler, 2011).

Although the tympanic thermometer evaluated in the current study utilizes a proprietary "ExactTemp®" measurement system" (designed to indicate when the thermometer is pointing at the tympanic membrane) there is still no certainty as to whether the thermometer was pointed at the tympanic membrane, or the wall of the auditory canal, which can lead to variability in the measurement (Huggins et al., 2012; Taylor et al., 2014). Even though infrared contact with the tympanic membrane can never be assured when using these types of thermometers, practitioner familiarity with tympanic membrane location within the auditory canal will lead to greater validity when using tympanic thermometry in the field (Taylor et al., 2014; Yeoh et al., 2017). Additionally, athlete familiarity with the sensation of a valid measurement will allow verification to the practitioner. Simple procedures such as applying a constant force and angle of a tympanic thermometer, removing excess cerumen (ear wax), and taking measurements in duplicate are also likely to lead to greater tympanic measurement validity.

Future research should endeavour to compare valid tympanic temperature measurement systems (such as the Braun ThermoScan® 7 used in the current study) against a telemetry pill system, outside of laboratory conditions.

3.6 Conclusion

The tympanic thermometer evaluated in the current study resulted in acceptable levels of agreement with the criterion measure and may provide a practical, minimally invasive alternative for measuring core temperature during exercise in the field. Caution should be taken if using such devices for temperature monitoring during a recovery period due to the tendency for tympanic devices to underestimate that of core temperature during recovery. Live monitoring using infrared thermal imaging cameras is not recommended to give accurate measures of skin temperature during exercise.

Chapter Four The relationship between physiological and performance variables during a hot/humid international rugby sevens tournament

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Prelude

To investigate factors that can impact upon the cumulative heat stress that elite rugby sevens athletes are subjected to during a rugby sevens tournament in hot and humid conditions, the characterisation of a tournament played in environmental conditions similar to those predicted at the Tokyo 2020 Olympic Games was undertaken. This chapter provided practitioners with important information regarding individual responses during rugby sevens competition in such an environment.

4.1 Abstract

To characterise physiological responses to competing in an international rugby sevens tournament played in hot/humid conditions, core temperature (T_c) and T_c predictors were collected from 11 elite men's rugby sevens athletes competing in the Oceania sevens tournament in Suva, Fiji. T_c, body mass change, sweat electrolytes, playing minutes, total running distance, high-speed running distance (HSD), psychrometric wet bulb temperature and exertional heat illness symptoms were collected pre, during and post games. Linear mixed models were used to assess the effect of T_c predictors on post-game T_c, along with differences in T_c across measurement periods. Compared to baseline on both tournament days, mean T_c was higher during all between game (recovery) measures (all d >1.30, p <0.01). On both tournament days, eight athletes reached a post-game T_c >39.0°C, with several athletes reaching >39.0°C during warm-ups. Mean post-game T_c was related to playing minutes, total running distance, HSD, and post warm-up T_c (all p < 0.01). The T_c during warm-ups and games regularly exceeded those demonstrated to be detrimental to repeated sprint performance (> 39°C). Warm-up T_c represents the easiest predictor of post-game T_c to control via time/intensity modulation and the use of appropriate pre- and per-cooling strategies. Practitioners should be prepared to modulate warm-ups and other heat preparation strategies based on likely environmental conditions during hot/humid tournaments.

4.2 Introduction

Rugby sevens is a team sport, characterised by repeated bouts of high intensity running, frequent contacts, sprints, skill, and spatial awareness (Ross et al., 2015a). International level rugby sevens athletes are reported to be large (mean body mass; 96 ± 7 kg) and lean (mean sum of 8 skinfolds; 62 ± 10 mm) (Ross et al., 2015c). A normal season for an international elite men's sevens team involves competing in ten tournaments worldwide, referred to as the World Rugby Sevens Series (WRSS). Each WRSS event normally consists of six games played across two days (pool play on day one, finals on day two) with each game consisting of two 7-min halves, with a 2-min halftime break. Most teams also normally warm up for ~30 min, the intensity and duration of which are likely to vary between teams, and the stage of competition (Taylor et al., 2019a). In total, this equates to five or six ~45 min exercise performances across two days (depending on placing after the pool stage). The WRSS match-play relative running demands are reported to be ∼113–120 $m \cdot min^{-1}$, often at high (∼19% ≥ 5 $m \cdot s^{-1}$) or very high (∼11% ≥ 6 $m \cdot s^{-1}$) speeds (Fowler et al., 2019; Ross et al., 2014) along with the inclusion of collision-based game actions per player per game, such as tackles and scrums (Ross et al., 2015a).

Although the game demands have been well characterised recently due to the increasing interest in the sport as a result of its recent inclusion in the summer Olympics, little is known regarding the impact of stressful environmental conditions on these athletes, particularly in an elite setting. The environmental conditions at these events can vary from oceanic (e.g., London/ Vancouver in local springtime) to arid-hot (e.g. Dubai in December). Performance in extreme/unpredictable environments is also possible, as seen recently when the WRSS experienced its hottest day ever, with on field temperatures reaching 45 °C at the 2020 Sydney tournament (unpublished tournament observations).

Previously, in an elite rugby sevens context it has been shown that individual athletes peak core temperature (T_c) during match play can reach > 39.0 °C in both temperate and hot conditions. The main predictor of peak T_c during games is reported to be the number of minutes played by each athlete (Taylor et al., 2019b). This same study indicated that T_c is highest during the final game of a given tournament, suggestive of a cumulative effect of repeated performance on T_c and hence the importance of incorporating cooling strategies across a tournament (Bongers et al., 2017; Henderson et al., 2021; Taylor et al., 2019b). Core temperatures of this magnitude are likely to be associated with environmental heat illness (EHI), which can impact both athlete performance and health (Casa et al., 2015).

Elevating muscle (and core) temperature is one of the key motivations for undertaking a warm-up before sprint exercise, with known relationships between sprint performance and the preservation of muscle temperature (Mohr et al., 2004). The caveat of this is that the impairment of repeated (intermittent) sprint exercise has been extensively described when T_c >39.0 °C (Beaven et al., 2018; Drust et al., 2005; Girard et al., 2015), implying that intermittent sprint athletes must balance optimal sprint performance with other game-specific factors. Repeated sprint performance is a key metric used by practitioners when describing the intensity of a rugby sevens game, most notably, practitioners commonly measure high-speed distance [HSD; an individually defined threshold speed; most commonly > $5 m \cdot s^{-1}$] (Ross et al., 2015a). The relationship between external load running demands (e.g. distance, HSD) and T_c has received limited application a rugby sevens context (Henderson et al., 2020a). Further, other physiologically important variables such as hydration status, sweat loss and sweat composition have never been characterised during an international elite rugby sevens tournament in hot/humid conditions.

Therefore, the purpose of the current study was 1) To characterise physiological and performance metrics that mediate T_c across two days of an international rugby sevens tournament performed in hot and humid conditions; 2) To characterise T_c itself during such a tournament. We hypothesised that i) external load data would predict post-game T_c, and ii) T_c would cumulatively increase during each tournament day.

4.3 Methods

Data were collected from 11 male athletes (age 24 ± 3 years; 94.3 ± 7.5 kg; height 187 ± 5 cm) from the same world champion international elite rugby sevens team during the 2018 Oceania rugby sevens tournament in Suva, Fiji. Six of the athletes were involved in the same years successful World Cup and Commonwealth games squads, three were regular full-time squad members and two were on seasonal training contracts. All athletes provided informed consent prior to testing, and ethical approval for the study was obtained through the institution's Human Research Ethics Committee. The Oceania rugby sevens tournament consisted of five games across two days (two games on Day One and three games on Day Two). Details of local time and environmental conditions during games are displayed in Table 4-1. Only data from periods where an athlete was involved in a subsequent game were included in the analysis, i.e., an athlete that played in Game One had their data included for all timepoints pre, during and post that game (until after the between-game measurement).

4.3.1 Core temperature (T_c)

Players ingested a core temperature telemetry pill (e-Celcius™ BodyCap, Caen, France) upon waking on each tournament day (~ 10 a.m. on day one, ~ 6 a.m. on day two), allowing for at least five hours before the first game time measurement. Telemetry pills were used for their practicality of collecting T_c data during a live tournament situation. Data was sampled every 30 s and downloaded at the end of the day via a wireless data receiver (e-Viewer, BodyCap, Caen, France). Due to technical difficulties with the wireless technology, some individual data was unable to be downloaded, hence the analysis presented in this manuscript relied upon manual collection of data (using a BodyCap wireless data receiver system) during pre-defined T_c measurement periods (pre-primer, post-primer, pre-warm-up, post warm-up, post-game, between game). Given that the current tournament (and all WRSS tournaments) involve(s) games scheduled at various times across a day from morning to evening, a small (by ~0.2-0.3 °C) influence of circadian variation in T_c was embedded in the current study design (West et al., 2014).

4.3.2 Sweat rate and sweat electrolytes

Before the start of the warm-up for game two and game four the skin of the right shoulder blade was cleaned with distilled water and dried, before adhesive gauze sweat patches (Tegaderm+Pad, 3M, Loughborough, UK) were applied directly to the skin. At the completion of these games, sweat patches were immediately placed into sealed containers and frozen at -20°C until analysis, whereby concentrations of sweat sodium, potassium and chloride were determined using absorbance photometry (Cobas C111 analyser, Roche, AG Basel Switzerland). Games two and four were chosen as they were the second match of each day, with similar environmental conditions. Body mass (wearing only underwear) was collected before the start of each warm-up and at the conclusion of each game using portable electronic scales (Tanita HD-351, Tanita Health Equipment H.K. Limited). Fluid intake was allowed *ad libitum* during each tournament day (not recorded); hence the reported body mass loss is despite *ad libitum* access to fluid. Signs and symptoms of exertional heat illnesses (EHI) were collected ~10 min after each game using verbal questions and answer via a modified survey instrument (Périard et al., 2017). Specifically, the athletes were asked if they had experienced (i) cramping; (ii) vomiting; (iii) nausea; (iv) light headedness or headache; (v) collapsing/fainting; or (vi) any other symptom that might relate to heat illness.

4.3.3 *Cooling strategies*

Cold-water immersion (CWI; using small rectangular pools of 2 m length x 2 m width x 1 m depth) was available *ad libitum* post-game with the duration of any exposure being recorded by a researcher. Athletes were instructed to sit in the pool immersed at least from the hip down. The pools were not circulatory and were cooled using the addition of ice, further, tournament officials maintained the temperature at ~12-15 °C using an immersible thermometer.

4.3.4 *Environmental conditions*

Psychrometric wet bulb temperature (WBTp) was calculated based upon measurements of temperature, humidity, wind speed and atmospheric pressure (Kestrel 4200, Nielsen-Kellerman Co, Boothwyn, PA, USA) that were obtained immediately prior to, during and post matches (from the end of the playing field). Due to the nature of the psychrometric ratio for a water-air system, the WBTp approximates the thermodynamic wet-bulb globe temperature (a traditional measure of human heat stress). The mean of these respective WBTp measurements at their associated timepoints were used in the analysis.

4.3.5 *External load*

Individual match running data (distance, high-speed distance) was collected using a wearable 10 Hz global positioning system (GPS; VxSport, Wellington, New Zealand). Individual game playing minutes for each athlete were collected by the team's performance analyst.

4.4 Statistical analysis

Linear mixed-effects analysis was performed using the *lme4* and *lmerTest* packages in R to assess the relationship between T_c and predictor variables (playing minutes, high-speed running distance (HSD), running distance, post warm-up T_c, and body mass difference). In different models, post-game T_c or Δ T_c was entered as the dependent variable with the other variables entered separately as fixed effects with player ID included as a random intercept to specify repeated measures for each athlete. P-values were obtained using Kenward-Roger approximation and approximate partial eta squared ($\eta^2 p$) effect sizes were converted from test statistics and degrees of freedom using the *effectsize* package in R. Cohen's *d* effect sizes (± 90% CL) were also determined to compare differences in predictor variables across different games (Game One – Five) and warm-ups (post warm-up one – five). Differences were described using standard thresholds of < 0.20 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). If the 90% CL overlapped positive and negative trivial (± 0.20) *d* values, the effect was deemed unclear. Paired t tests were used to analyse differences in sweat electrolyte concentration between games two and four, these data are reported as mean ± SD, with an alpha level of 0.05.

4.5 Results

Group mean data for environmental conditions, playing min, running distance, HSD, and body mass loss, along with their quantitative differences are presented in Table 4-1. Group mean differences and individual temperatures across pre-defined measurement periods for Day One and Day Two are shown in Figure 4-1. Figure 4-2 shows group mean and individual Δ T_c across each measurement period.

Predictors of post-game T_c: Linear mixed-effects analysis established that playing minutes, post warm-up T_c, total running distance and HSD were all significant predictors of post-game T_c (all $p \leq 0.001$, all $\eta^2p \geq 0.14$), whereas body mass change was not; see Table 4-2 for full details on each predictor.

Predictors of post-game T_c when playing min >6 min: Linear mixed-effects analysis established that only total running distance was a significant predictor of post-game T_c when playing min >6 min ($p = 0.001$, $\eta^2p = 0.16$), see Table 4-3 for full details on each predictor.

Game Three included a 4.5 min injury break during the second half, whereby all athletes were required to remain on the field in a similar manner to a half time break. Game Five (the tournament cup final) went to overtime (the scores were tied at the end of full time). In this instance, there was a two-min break between full time and overtime, and the overtime lasted for a further 3.8 minutes (golden point rules). There were no differences in sweat sodium (41 ± 16; 39 ± 15 $mmol \cdot L^{-1}$), potassium (4 ± 1; 4 ± 1 $mmol \cdot L^{-1}$), or chloride (34 ± 13; 32 ± 12 $mmol \cdot L^{-1}$) between Game Two and Game Four (all $p > 0.05$). Mean body mass for each combined warm-up and game period (despite *ad libitum* access to fluid) loss was *at least* -0.5 kg, full results are shown in Table 4-1. One symptom (light headedness or headache) of EHI was reported by one athlete on two occasions (post-Game Four; post-game T_c = 39.6 °C, post-Game Five; post-game T_c = 40.0 °C). No other athletes reported any EHI symptoms throughout the tournament.

Table 4-1: Local time, environmental conditions, playing minutes, running distance (m), game high speed distance (m), and pre- post game body mass loss (kg) for one international team during all games (1-5) at the Oceania men's rugby sevens tournament.

	Game # (local time)	**Game Temp. (°C), RH (%), WBT$_p$ (°C)**	**Playing Minutes (min)**	**Running Distance (m)**	**High Speed Distance (m)**	**Body mass loss (kg)**
Day One	Game 1 (16:36)	31.3; 71%; 26.4	10.5 (2.8, 16.2)	1409 (1015, 1891)	115 (62, 205)	-0.5 (-1.6, 0.1)
	Game 2 (19:46)	29.0; 73%; 25.0	8.8 (2.4, 15.1)	1300 (803, 1786)	147 (91, 197)	-0.8 (-1.6, 0.1)
Day Two	Game 3 (11:26)	30.4; 73%; 26.1	9.8 (6.6, 16.0)	1138 (708, 1533)	117 (48, 271)	-0.5 (-1.1, 0.1)
	Game 4 (15:18)	29.9; 75%; 25.3	9.5 (2.5, 14.7)	1190 (789, 1557)	89 (50, 145)	-0.6 (-1.3, 0.1)
	Game 5 (20:20)	26.0; 81%; 23.6	11.9 (7.4, 20.6)	1410 (1012, 2237)	154 (107, 308)	-0.5 (-1.4, 0.1)
Game 1 vs. Game 2	-	-	-0.31 ± 0.77 *Unclear*	-0.29 ± 0.80 *Unclear*	0.61 ± 0.77 ***Moderate***	-0.52 ± 0.77 *Unclear*
Game 3 vs. Game 4	-	-	-0.06 ± 0.73 *Unclear*	-0.17 ± 0.73 *Unclear*	0.58 ± 0.72 ***Small***	-0.28 ± 0.73 *Unclear*
Game 3 vs. Game 5	-	-	0.48 ± 0.71 *Unclear*	1.06 ± 0.73 ***Moderate***	0.61 ± 0.72 ***Moderate***	-0.10 ± 0.71 *Unclear*
Game 4 vs. Game 5^	-	-	0.33 ± 0.74 *Unclear*	0.47 ± 0.73 ***Small***	0.97 ± 0.72 ***Moderate***	0.15 ± 0.73 *Unclear*
Game 1 vs. Game 5^	-	-	0.27 ± 0.73 *Unclear*	-0.02 ± 0.72 *Unclear*	0.48 ± 0.72 *Unclear*	0.04 ± 0.76 *Unclear*

Data (except local time and environmental conditions) are represented as mean (range). Differences between games (shaded panels) are represented as standardised effect sizes (Cohen's d ± 90% confidence limits). ^Game 5 was the cup final which included a total of 3.8 min of overtime. RH = relative humidity; WBTp = Psychrometric Wet Bulb Temperature

Table 4-2: Results of linear mixed-effects analysis assessing the effect of playing minutes, game high speed distance (m), running distance (m), post warm up core temperature (T_c; °C), and body mass loss (kg) on individual post-game T_c across all games for one international team during the 2018 Oceania men's rugby sevens tournament.

		Estimate	**Standard Error**	**T statistic**	**p value**	**F value**	**Effect size (η^2p)**
Playing minutes (min)	Intercept	38.4	0.137	279.56	<0.0001	19.788	0.29 [0.13, 0.45] *large*
	Slope	0.052	0.011	4.625	<0.0001	-	-
High speed distance (m)	Intercept	38.6	0.138	279.3	<0.0001	6.967	0.14 [0.02, 0.30] *medium*
	Slope	0.003	0.001	2.777	0.001	-	-
Distance (m)	Intercept	38.1	0.1903	200.34	<0.0001	21.56	0.33 [0.15, 0.49] *large*
	Slope	0.0006	0.0001	4.77	<0.0001	-	-
Post warm up T_c (°C)	Intercept	25.7	4.88	5.259	<0.0001	7.076	0.14 [0.02, 0.30] *medium*
	Slope	0.345	0.127	2.715	0.009	-	-
Body mass loss (kg)	Intercept	38.8	0.124	313.2	<0.0001	2.073	0.04 [0.00, 0.17] *small*
	Slope	0.21	0.141	1.507	0.139	-	-

Table 4-3: Results of linear mixed-effects analysis assessing the effect of playing minutes, game high speed distance (m), running distance (m), post warm up core temperature (T_c; °C), and body mass loss (kg) on individual post-game T_c across all games for one international team during the 2018 Oceania men's rugby sevens tournament. Only data for athletes that played > 6 min in any game is included.

		Estimate	**Standard Error**	**T statistic**	**p value**	**F value**	**Effect size ($\eta^2 p$)**
Playing minutes (min)	Intercept	38.8	0.194	199.51	<0.0001	2.4714	0.06 [0.00, 0.22] *medium*
	Slope	0.025	0.015	1.666	0.104	-	-
High speed distance (m)	Peak T_c	38.9	0.144	269.9	<0.0001	6.967	0.03 [0.00, 0.18] *small*
	Slope	0.001	0.001	1.173	0.248	-	-
Distance (m)	Intercept	38.5	0.1903	165.9	<0.0001	6.89	0.16 [0.02, 0.34] *large*
	Slope	0.0006	0.0004	2.73	0.001	-	-
Post warm up T_c (°C)	Intercept	30.7	4.43	6.912	<0.0001	3.467	0.10 [0.00, 0.28] *medium*
	Slope	0.219	0.115	1.899	0.07	-	-
Body mass loss (kg)	Intercept	39.0	0.109	357.38	<0.0001	0.352	0.01 [0.00, 0.12] *small*
	Slope	0.08	0.128	0.632	0.531	-	-

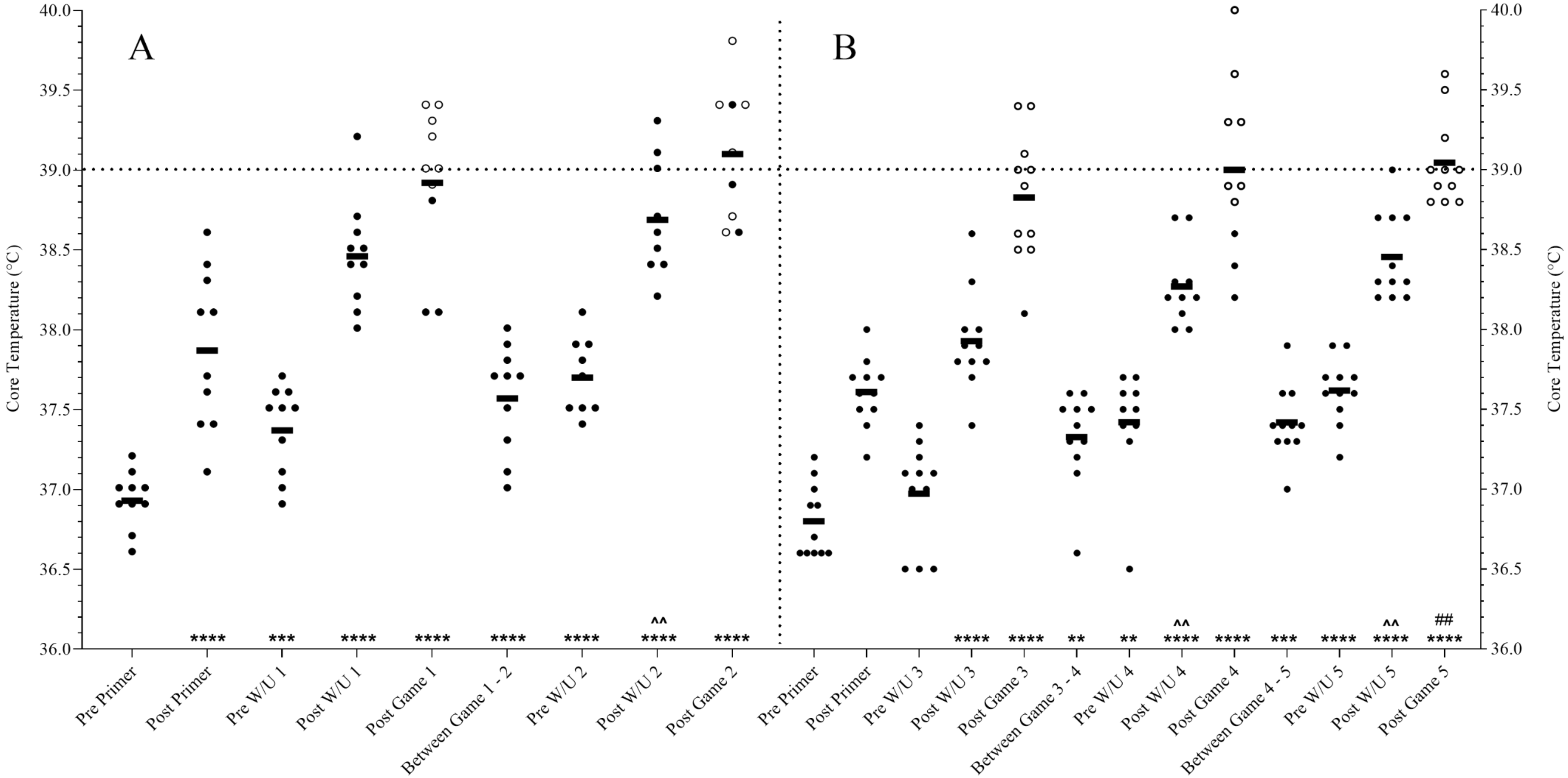

Figure 4-1: Individual core temperature (T_c: °C) across pre-defined measurement periods during day one (panel A) and day two (panel B) for one international team during the Oceania rugby sevens tournament. The solid black line represents the group mean, while individual responses are represented as closed black squares (playing min <6 min) or open white circles (playing min >6 min). Symbols above the x-axis represent standardised effect sizes (Cohen's *d*) for the following comparisons: * = compared to a within-day baseline; ^ = compared to the previous warm-up; # = compared to game 3. The number of symbols represent the size of the effect; 1 = small, 2 = moderate, 3 = large, and 4 = very large. The dotted line at 39.0 °C represents a T_c threshold whereby a T_c above this has been demonstrated to reduce repeated sprint performance. W/U = warm-up.

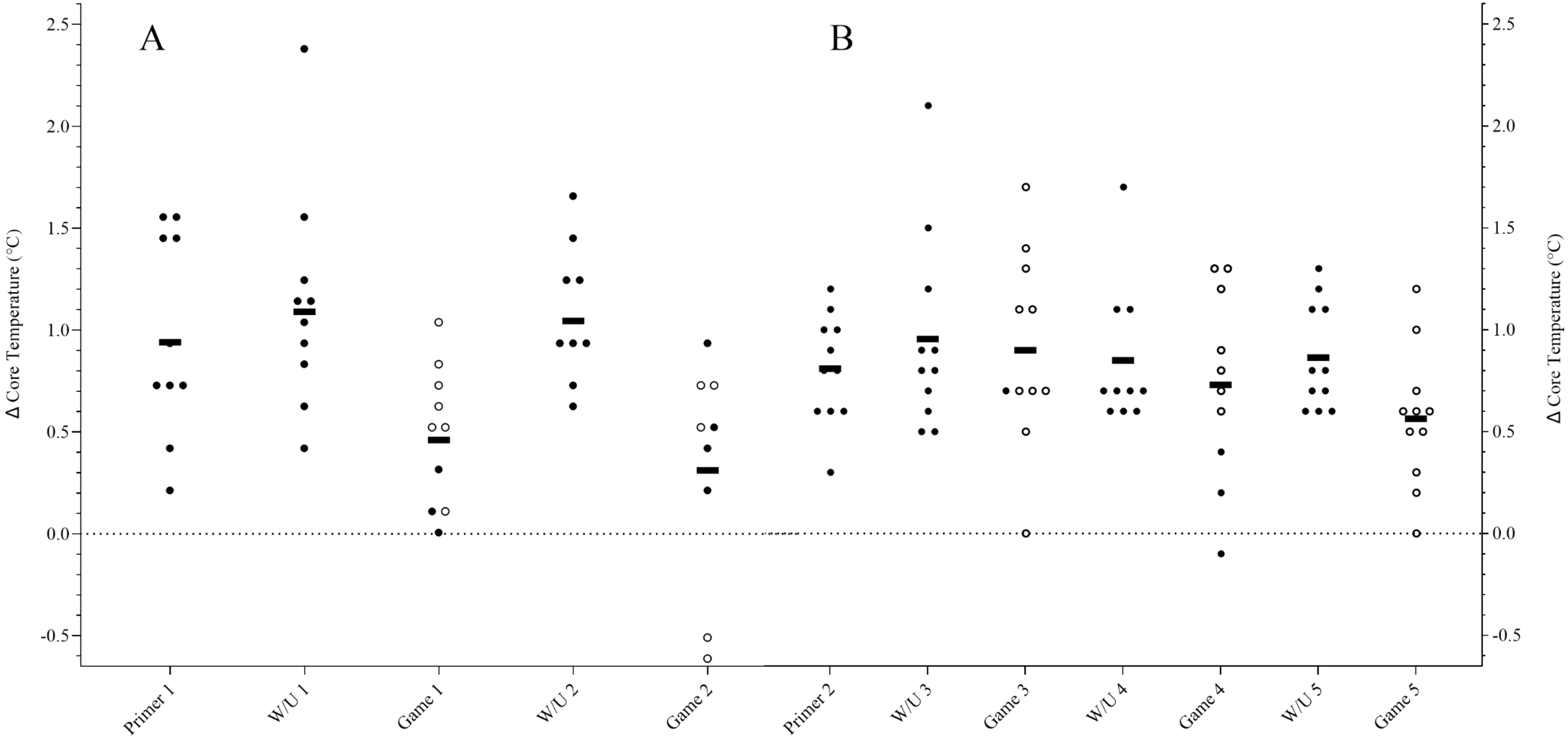

Figure 4-2: Change in individual core temperature (ΔT_c: °C) across pre-defined measurement periods during day one (panel A) and day two (panel B) for one international team during the Oceania rugby sevens tournament. W/U = warm-up

4.6 Discussion

The current study demonstrated that commonly measured variables such as playing minutes, HSD, and total distance can significantly predict post-game T_c during an international rugby sevens tournament played in hot and humid conditions. Furthermore, post warm-up T_c significantly predicted post-game T_c, neither of which has previously been described. During each tournament day sequential increases in mean T_c post warm-up were shown and all post-baseline measures were greater than baseline on day one and day two, respectively. Both findings are indicative of a cumulative increase in T_c across the tournament as hypothesised, particularly during non-competition exercise. These novel findings have important implications for practitioners, considering that distance and playing minutes are readily available metrics.

Throughout the course of the current two-day tournament, numerous athletes had significantly elevated T_c, with nearly three-quarters of the athletes experiencing T_c approaching and above those associated with impaired repeated sprint performance [39 °C] (Girard et al., 2015), and EHI symptoms [>39.5 °C] (Racinais et al., 2015). Notably, some of these instances of $T_c \geq 39.0$ °C occurred during warm-ups, while four individuals reached a T_c of > 39.0 °C on more than one occasion. Previous investigations have demonstrated that playing minutes have a significant effect on individual post-game T_c during international rugby sevens tournaments in both male (Taylor et al., 2019b) and female (Henderson et al., 2020a) athletes, even in modest environmental conditions. This relationship is also present in the current study ($p < 0.0001$, $\eta^2p = 0.29$) , with game time being > 6 min on 16/17 occasions when post-game T_c was > 39.0 °C. Interestingly, when game time > 6 min, distance remained a significant predictor of post-game T_c in the current study ($p = 0.001$, $\eta^2p = 0.16$), whereas Henderson et al. (2020a) found no association between post-game T_c and any external load variable during an elite female rugby sevens tournament.

The description of the relationship between post-game T_c and commonly measured external load data (distance, HSD) is a novel aspect of the current study. Total running distance was the best external load predictor, with the slope of temperature change during the current study (an increase of 0.6 °C per 1000 m total running distance or 0.05 °C per playing min) providing practitioners with an estimate of how these variables may influence post-game T_c. Moreover, of all the predictors of post-game T_c, post warm-up T_c has the greatest potential to be modulated via altering the time and intensity of a warm-up period and/or via the use of pre- and per-cooling strategies. This is particularly relevant considering that within both the current study and Taylor et al. (2019b), a cumulative increase in T_c across tournament days was evident, with the final games of each tournament day associated with the highest T_c demands. Taken together, these data should provide practitioners confidence to develop individualised tournament load management and cooling protocols that aim to limit prolonged exposure to high core temperatures, thus optimising player readiness.

Heat acclimation (HA) (particularly longer-term HA) is well regarded as the most important intervention to reduce physiological strain and optimise performance in the heat (Racinais et al., 2015), however, in the current investigation, no form of HA or mandated cooling practises (such as pre-, per- and post-cooling) were undertaken. It is expected that HA would result in a decrease in baseline T_c, along with a decrease in the slope of T_c rise (Tyler et al., 2016). There have been limited investigations into how HA can synchronise into an elite rugby sevens environment due to the competing influences of other training demands, travel and tournaments (Casadio et al., 2017). With traditional HA recommendations being largely unfeasible in an elite rugby sevens setting, practical solutions, such as wearing additional clothing during training have been shown to provide an increased thermal stimulus, without impacting external running load during training sessions (Henderson et al., 2020b). In turn, utilising common pre- and per-cooling strategies such as the ingestion of ice slushy (Beaven et al., 2018; Brade et al., 2014), application of ice-towels (Duffield et al., 2009; Minett et al., 2012) and ice vests pre and during warm up (Taylor et al., 2019a) has been suggested as best practice in team sports (Aldous et al., 2018; Tyler et al., 2015). Incorporating such match day cooling strategies may further mitigate the rise in T_c seen in the current study.

Further investigation of the data from the athlete in the current study with EHI symptoms revealed that on both occasions, the athlete spent > 55 % of those games with a T_c of > 39.5 °C. The development of EHI can be complicated due to the myriad risk factors associated with the illness (e.g., current or recent illness, previous EHI history, concussion, HA status) (Casa et al., 2015). This indicates the importance of having explicit EHI screening processes to identify individual athletes within a team who may be at risk of EHI, along with targeted heat management strategies that principally involve heat acclimation/ acclimatisation and aggressive match day cooling, as per consensus recommendations for competing in hot environments (Casa et al., 2015; Racinais et al., 2015). The sweat electrolyte concentrations seen in the current study are similar to those reported in a cohort of elite rugby union (15-a-side) athletes (Black et al., 2018), along with previous cross-sectional studies of athletes in other team sports such as soccer (Shirreffs et al., 2005), American football (Stofan et al., 2003), and indoor sports (Hamouti et al., 2010).

In the current investigation, between game T_c was above baseline on all occasions. Post-cooling (via cold water immersion) was available for use in the current study; however, *ad libitum* use by athletes was minimal (only used by 4/11 athletes throughout the tournament; every exposure was < 75 s), and hence insufficient to produce any acute T_c decrease, after drop in T_c (Bongers et al., 2017), or decrease of indices of cumulative fatigue (Montgomery et al., 2008). CWI has an unrivalled ability to decrease T_c, and easily obtainable external load data (playing minutes, distance) are most likely to predict post-game T_c. Hence, practitioners should consider these external load variables, along with the known relationship between body mass and exercise heat stress (Gibson et al., 2017) to individualise the prescription of cooling strategies (such as prescribing CWI time per playing min or total distance).

Although external load data for the current tournament indicates that the running demands were consistently within 10% of those previously shown for the WRSS (Ross et al., 2015a), the Oceania rugby sevens tournament involves teams not currently qualified for the WRSS. This, along with the small sample size, taken from only one team may limit the generalisability of the current findings. Future research should endeavour to incorporate repeated measures across multiple WRSS tournaments and/or teams to gain a more robust assessment of the relationships seen in the current study. The current findings focus on physiological factors (particularly T_c) that are likely to influence rugby sevens performance, however, successful performance in rugby sevens requires a combination of physical, technical, and tactical proficiencies. How elevated game T_c can impact the technical and tactical proficiencies in rugby sevens is currently unknown and should be elucidated in future research, particularly considering the known relationship between excessive T_c rise and decreased cognitive function shown elsewhere (Bain, 2015; Shibasaki et al., 2017).

4.7 Practical implications

- Practitioners and athletes should be prepared to adjust non-competition exercise (i.e., warm-ups) when competing in challenging environmental conditions.
- Rugby sevens (and other similar team-sport) practitioners should incorporate heat management strategies into their preparation. Most importantly, this should include a sports-specific heat acclimation process along with appropriate cooling strategies.
- Commonly measured external load data could be useful to individualise recovery protocols for repeated performances across a tournament.

4.8 Conclusion

Throughout an international rugby sevens tournament played in hot/humid conditions T_c during warm-ups and games regularly exceeded 39 °C. Post-game T_c can be predicted by playing minutes, total running distance, and post warm-up T_c. Practitioners should be prepared to modulate these variables when competing in hot/humid environmental conditions, along with including team-specific heat acclimation and appropriate pre- and per-cooling strategies to maximise game preparation. Future research should focus on the development and assessment of best practise cooling and heat acclimation strategies in an elite rugby sevens context, along with providing similar data from elite females performing in hot and humid conditions.

Chapter Five Evaluation of an off-feet heat response test for elite rugby sevens athletes

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Prelude

While Chapter Four provided important information regarding the characteristics that determine elevated T_c across a rugby sevens tournament played in hot and humid conditions, assessment of the adverse impacts of heat stress in a controlled environment provides important information to practitioners to individualise heat management strategies. Furthermore, the evaluation of an off-feet heat response test allows for greater information as to the specificity of such a test during studies later in the thesis.

5.1 Abstract

A heat response test (HRT) assesses thermoregulatory responses to heat stress and athlete readiness to perform in hot conditions. However, testing is often not sport-specific, and is challenging to incorporate into elite team-sports schedules due to competing training priorities. Seven non-heat acclimated elite rugby sevens undertook two running tests designed to be specific to the demands of rugby sevens in temperate (20 °C, 50% RH; RUN:AMB), and hot (35 °C, 80% RH; RUN:HOT) conditions. In addition, athletes performed a cycling-based HRT (CYCLE:HOT) designed to provide similar physiological stimulus as RUN:HOT, without the associated mechanical load. Physiological and perceptual variables were monitored throughout each test. Mean tympanic temperature (T_{Tymp}), heart rate (HR), thermal sensation, rate of perceived exertion, and sweat loss significantly increased, while thermal discomfort and performance decreased in RUN:HOT compared with RUN:AMB, (all $d > 1.40$; $p < 0.05$). Significant reductions in mean T_{Tymp} and HR were evident in CYCLE:HOT compared with RUN:HOT (both $d > 1.10$; $p < 0.05$), whereas there were no clear differences in any perceptual variables. Mean peak T_{Tymp} was 39.5 ± 0.5 °C in RUN:HOT and 38.8 ± 0.4 °C CYCLE:HOT, respectively. Acute heat stress is detrimental to performance in non-heat acclimated elite rugby sevens athletes. High-intensity cycling in the heat induces thermal strain sufficient to drive adaptation, and can replicate the perceptual, but not the physiological stress associated with high-intensity running in the heat. Cycling-based HRT could be used to avoid additional mechanical load associated with running-based heat testing.

5.2 Introduction

Heat response (or heat stress) tests (HRT) are used to assess athletes' ability to cope with the physiological and perceptual demands of exercising in the heat, along with their capacity to perform in hot conditions. HRT are commonly carried out at the beginning and end of a heat acclimation (HA) protocol to assess resulting adaptations, and also in the following days/weeks following HA to assess the persistence of adaptations (Tyler et al., 2016). Practitioners also use HRT as one-off assessments of an athlete's ability to cope with the demands of performance in the heat, including those who are returning to training in the heat following exertional heat illness (Johnson et al., 2013). In a sporting context, HRT generally contain a sustained period of fixed-load work, followed by a component of maximal exertion or time to exhaustion (such as a time-trial), which provides a performance measure in the heat (Daanen et al., 2018). Current guidelines recommend that HA protocols (and hence HRT) should be specific to the demands of an athlete's sport (Racinais et al., 2015). This specificity permits simple integration of heat stimulus into an existing training schedule, and allows athletes to experience heat stress in a situation that reflects their competitive environment which may be useful for specific post-acclimation performance (Casadio et al., 2017; Racinais et al., 2015; Wingfield et al., 2016). Many HA protocols have been designed for endurance athletes, which is reflected in the design of most HRT's (Tyler et al., 2016). In contrast, HA and HRT has limited previous assessment in team sport contexts, particularly at an elite level (Garrett et al., 2019; Pethick et al., 2018).

Rugby sevens is an Olympic team sport characterized by repeated bouts of high-intensity running, frequent contacts, sprints, skill, and spatial awareness, played over two 7-min halves, with seven players per team (Ross et al., 2015a). Players have been reported to cover a total of ~1500 m in one game, with ~250 m being above an arbitrarily assigned high-speed running threshold of 5.0 $m \cdot s^{-1}$, and maximal running velocities of 8.0 to 8.5 $m \cdot s^{-1}$ (Ross et al., 2015a). Every season, between December to May, the International Rugby Board (IRB) conduct the ten tournament World Rugby Sevens Series (WRSS). These international competitions are often played in hot summer environments, with temperatures as high as 45 °C (113 °F) recorded during a recent tournament in Sydney, Australia (February 2020, unpublished field observations). The combination of challenging environmental conditions and high relative exercise intensity likely combine to present a thermoregulatory challenge during elite rugby sevens competition (Gonzalez-Alonso et al., 2008), as demonstrated in a previous investigation, where high (39.9 °C) individual peak T_c values were recorded during a hot/humid tournament (Taylor et al., 2019b). Furthermore, considering that the (delayed) Tokyo 2020 Summer Olympics are predicted to be the hottest on record (Kakamu et al., 2017), the importance of appropriate team and individual specific heat management strategies for international rugby sevens teams are clearly indicated (Daanen et al., 2018; Racinais et al., 2015).

Within a full-time professional rugby sevens season, it is common practice to conserve running load for specific training. In this case, off-feet conditioning is often used to compliment running exercise in order to obtain/sustain cardiovascular and metabolic adaptations, without the mechanical load-bearing stress that running exerts (Hamlin et al., 2017; Wehbe et al., 2015). Therefore, the aims of the current research were to evaluate an off-feet (cycling) HRT, that would be acceptable for practitioners to include within the normal training week of an international elite rugby sevens team. The off-feet test was designed to provide a similar physiological stimulus as a running test, while also being specific to the physiological demands of elite rugby sevens. Furthermore, the research aimed to evaluate responses between a ambient environment (20 °C, 50% RH) and the thermally challenging conditions expected at the Tokyo 2020 Olympics (35 °C, 80% RH).

5.3 Materials and methods

5.3.1 Subjects

Data was collected from seven non-heat acclimated elite male rugby sevens athletes (age: 25 ± 3 years; body mass 95.3 ± 6.5 kg; height 190 ± 3 cm; all mean ± SD) of a single 2018-19 WRSS international team after signing written informed consent. The procedures of the study were approved by the Human Research Ethics Committee of the University of Waikato (HREC2018#64). Athletes were asked to consume the same food and abstain from alcohol and caffeine in the 12-h before each testing session. All trials took place in local springtime conditions (mean daytime high ~18 °C) throughout the teams' pre-season to avoid any natural heat acclimatization. Participants refrained from strenuous exercise outside of the laboratory for 48-h before each testing session.

5.3.2 Experimental design

Participants undertook three tests across three consecutive weeks, including a control condition (RUN:AMB) and two heat response tests (HRT; RUN:HOT, CYCLE:HOT). The two RUN conditions were completed first in a randomized cross-over design, while the CYCLE:HOT condition was completed on week three for all participants. All HRTs were performed in an environmental chamber set at 20 °C, 50% RH for the RUN:AMB condition and 35°C, 80% RH for the RUN:HOT and CYCLE:HOT conditions. Participants performed all testing sessions at the same time of day (Monday a.m.) across three weeks to account for circadian rhythms (Reilly & Brooks, 1986) and weekly training schedules. During all conditions, participants consumed a standardized amount of 6% carbohydrate sports drink (Gatorade, The Gatorade Company, Inc. Chicago, IL., USA) at room temperature (200 mL pre-warm-up, 200 mL post warm-up, 120 mL at half-time, 120 mL pre time-trial; 640 mL total).

5.3.3 RUN Heat response tests

Seven days before the first running test all participants completed a familiar 1.2 km shuttle run test (Bronco) (Kelly & Wood, 2013) as part of their normal pre-season assessment. Individualized interval speed during the RUN HRT was equivalent to 110% of each individual's average Bronco speed, as determined from the 1.2 km shuttle run test.

Participants entered the environmental chamber and completed a 19-min progressive-intensity, standardized warm-up (see Figure 4-1) followed by a repeated interval protocol and a 1200 m time trial (TT). The repeated interval protocol consisted of 30-s running at 110% of each individual's average Bronco speed (18.3 ± 0.8 km·h^{-1}), followed by 40-s rest, repeated 12 times with a 2-min half-time break after interval 6. Immediately following every 2nd interval, participants also performed five down-ups (to simulate rucking type movements in rugby sevens). The design and content of the repeated interval protocol was chosen as it replicates game average high-intensity running volume, work: rest ratios (30 s: 40 s), and dynamic rucking type movements in rugby sevens (~15 per match) (Ross et al., 2015a). The 1200 m TT was included as it is the same distance as many teams usual running performance test (Bronco), providing a simple and familiar metric for athletes and practitioners. All running was undertaken on a calibrated motorized treadmill (Life Fitness 95T Elevation, Life Fitness, Inc. Rosemont, IL. USA.) set at a 1% incline, which most accurately reflects the energetic cost of outdoor running (Jones & Doust, 1996). During the 1200 m TT, the display monitor of the treadmill was covered, and the participants were instructed to control the speed of the treadmill themselves, with distance being the only external feedback given verbally by a researcher at 200 m intervals.

5.3.4 CYCLE:HOT Heat response test

The CYCLE:HOT HRT was performed on a calibrated cycle ergometer (WattBike Ltd, Nottingham, UK) and consisted of the same time structure as the run tests, with exercise intensity being standardized using relative power output [watts per kg of body mass; ($W \cdot kg^{-1}$); see Figure 4-1]. During the 30-s intervals, participants were asked to maintain a power output of 3.0 $W \cdot kg^{-1}$ followed by 40-s rest, repeated 12 times with a 2-min half-time break after interval 6. Immediately following every 2nd interval, participants also performed six down-ups. A power output of 3.0 $W \cdot kg^{-1}$ was chosen as this reflected individual mean HR during the 1.2km shuttle run test (as described above) in pilot testing. The performance test during the CYCLE:HOT was a 4-min TT whereby the monitor of the cycle ergometer was covered, and verbal cues given by a researcher at 1000, 2000, 2500, and 2800 m. A 4-min TT was chosen as this distance takes a similar time to the running 1.2 km shuttle run test, participants were familiar with this cycle test as it is commonly used as an off-feet conditioning session during their normal training, and it has been shown to have high level of test-retest reliability (CV < 3%) (Driller et al., 2014).

5.3.5 Physiological measurements

Tympanic temperature (T_{Tymp}; Braun ThermoScan® 7 IRT6520, Braun GmbH, Kronberg, Germany) and Heart rate (HR; Polar H10, Polar Electro Oy, Kempele, Finland) were sampled at 0 min, post warm-up, after intervals 3 and 6; at the end of half time; after intervals 9 and 12; Pre TT and End TT. The mean of values collected after intervals 3 and 6 was taken to calculate the first half measurement, likewise for the second half with intervals 9 and 12 (as shown in Figure 4-2). Each T_{Tymp} measurement was sampled in duplicate, the mean of which was recorded for analysis. T_{Tymp} was chosen as our method of assessing body temperature as it has been previously demonstrated acceptable agreement with assessment of core temperature via telemetry pill when exercising in the heat (Fenemor et al., 2020) Each researcher was trained to take to measure T_{Tymp} the same way, as previously described (Fenemor et al., 2020).

Before the start of each test the skin of the right shoulder blade was cleaned with distilled water and dried, before adhesive gauze sweat patches (Tegaderm+Pad, 3M, Loughborough, UK) were applied. At the completion of each test, sweat patches were immediately placed into sealed containers and frozen until analysis. Sweat sodium concentration was determined using absorbance photometry (Cobas C111 analyser, Roche, AG Basel Switzerland). To estimate sweat loss, towel-dried, nude body mass (NBM) was recorded to 0.1 kg using digital scales (Seca 877, Seca, Hamburg, Germany) before and immediately after each session, this value was adjusted for ingested liquid during the test (640 ml).

Condition		**Warm Up**		**1st Half**	**H/T**	**2nd Half**		**Time-Trial**
RUN:AMB	##		##		#		#	1200m
RUN:HOT	##		##		#		#	1200m
CYCLE:HOT	##		##		#		#	4-min

	5-min dynamic stretching (DS), 4-min run at 10 $km\cdot h^{-1}$, 2-min DS, 2-min run at 13 $km\cdot h^{-1}$, 2-min DS, 30 s run at 16 $km\cdot h^{-1}$, 1-min rest, 30 s run at 16 $km\cdot h^{-1}$, 2-min rest
	5-min DS, 4-min cycle at 1.5 $W\cdot kg^{-1}$, 2-min DS, 2-min cycle at 2.0 $W\cdot kg^{-1}$, 2-min DS, 30 s cycle at 3.0 $W\cdot kg^{-1}$, 1-min rest, 30 s cycle at 3.0 $W\cdot kg^{-1}$, 2-min rest
	30 s running @ 110% mean bronco speed: 40 s rest x 6; 6x down-ups after every 2nd interval.
	30 s cycling @ 3 $W\cdot kg^{-1}$: 40 s rest; x 6. 6x down-ups after every 2nd interval.
# = 120 ml Sports Drink; ## = 200 ml Sports Drink; H/T = 2-min Half Time	

Figure 5-1: Schematic of the Heat Response Test (HRT) protocols.

5.3.6 Perceptual measurements

Rating of perceived exertion (RPE; 6-20 scale) (Borg, 1970), thermal sensation (TS; 1-13 point scale) (Gagge et al., 1967), thermal discomfort (TDC; 1-10-point scale) (Gagge et al., 1967) and thirst sensation (Thirst; 1-9 point scale) (Riebe et al., 1997) were collected at the same time points described above for physiological measurements.

5.3.7 Statistical analysis

Raw data in tables and text are presented as mean ± SD with the mean differences and uncertainty of estimates shown as Mean Difference (MD) ± 90% confidence limits (CL). For all variables, the mean of all data points was calculated and used in the corresponding analysis, presented in Table 5-1. Each comparison (RUN:HOT vs RUN:AMB; RUN:HOT vs CYCLE:HOT) was analysed separately to assess the size of effect (Cohens *d* effect sizes; ES), statistical significance (resulting from paired sample t-tests), and practical meaningfulness using specifically designed customizable spreadsheets (Hopkins, 2006). If the 90% CL overlapped positive and negative trivial (+/- 0.20) ES values, the effect was deemed unclear. Cohens *d* ES and 90% CL were characterized using standard thresholds of < 0.20 trivial, 0.21 – 0.60 small, 0.61 – 1.20 moderate, 1.21 – 2.0 large, and > 2.0 very large (Hopkins, 2007). T_{Tymp} was further analysed using two-way repeated measures ANOVA to determine if there were differences between conditions and across time using the Šídák – Bonferroni correction for pairwise multiple comparisons. Normality and homogeneity of variance of residuals were checked using quantile-quantile (Q-Q) and scatter plots, which were deemed plausible in each instance. The smallest worthwhile change (SWC) for each variable was presented as it provides information regarding practical meaningfulness, which is most relevant to sport performance (Buchheit, 2016). The smallest worthwhile change (SWC) for thermoregulatory and perceptual variables were determined from a recent meta-analysis on responses to HA (Tyler et al., 2016) and are as follows; resting T_{Tymp} (0.2 °C), exercise T_{Tymp} (0.3 °C), submaximal HR (9 bpm), peak HR (12 bpm), thermal sensation (0.9 AU) thermal discomfort (0.9 AU), thirst (0.9 AU), and RPE (1.0 AU). The SWC we used for resting and exercise T_{Tymp} were based upon the SWC that Tyler et at., (2016) reported for core temperature (T_{core}), as T_{Tymp} is a valid measure of T_{core} when exercising in the heat (Fenemor et al., 2020). The SWC for the time-trial in each condition was estimated by taking one third of the population coefficient of variation CV % for each measurement, based on previous reliability data collected in our lab (1200 m TT SWC = 2.2%; 4-min TT SWC = 2.7%). Magnitudes of the smallest worthwhile change (fSWC) as follows; small (1.1 – 2.9 x SWC), moderate (3.0 – 5.9 x SWC), large (6.0 – 9.9 x SWC) and very large

(>10 x SWC). For fSWC data, quantitative chances of higher or lower differences were evaluated qualitatively as follows; 75% to 95%, *likely*; 95% to 99%, *very likely*; and >99%, *most likely*.

5.4 Results

During RUN:HOT, mean T_{Tymp}, HR, TS, RPE, sweat loss, and time to complete the 1200 m TT were significantly higher, and mean TDC was significantly higher (less comfortable) than RUN:AMB (Table 5-1). During CYCLE:HOT, mean T_{Tymp} and HR were significantly lower than RUN:HOT (Table 5-1). Mean differences, effect sizes and statistical significance are presented in Table 5-1 and the magnitude of these differences are presented in Figure 5-3: A-B.

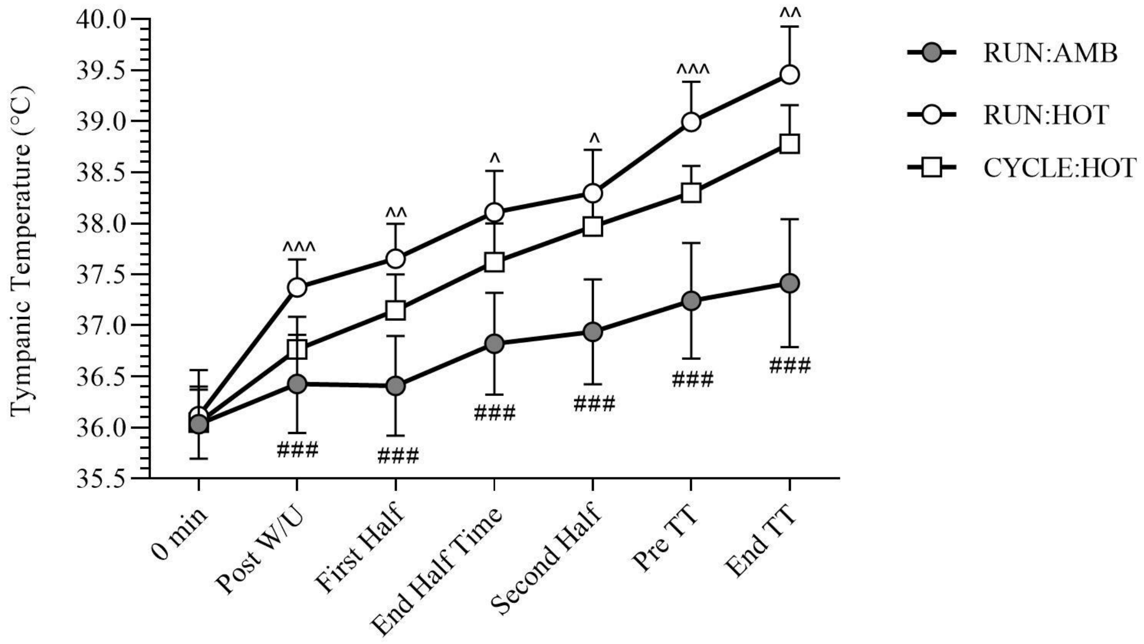

Figure 5-2: Mean (± 90% CL) Tympanic Temperature (°C) at each measured timepoint for the three interventions. Characters displayed above/below symbols represent differences between the two comparisons as follows; # = RUN:AMB different to RUN:HOT; ^ = RUN:HOT different to CYCLE:HOT. The presence of a symbol indicates p < 0.01. The likelihood of the observed effect exceeding the smallest worthwhile difference (0.3 °C) are represented by the number of symbols; 1 = likely, 2 = very likely and 3 = most likely.

Table 5-1: Grouped mean (± SD) and mean differences [mean difference ± 90% confidence limits (Cohens d)] for all variables for RUN:AMB, RUN:HOT and CYCLE:HOT Heat Response Tests.

	RUN:AMB	RUN:HOT	CYCLE:HOT	RUN:HOT vs. RUN:AMB	RUN:HOT vs. CYCLE:HOT
T_{Tymp} (°C)	36.9 ± 0.3	38.3 ± 0.3	37.8 ± 0.2	1.4 ± 0.4 (3.09) *very large****	0.5 ± 0.3 (1.44) *large****
HR (bpm)	150 ± 5	164 ± 7	152 ± 6	14 ± 8 (1.49) *large**	12 ± 9 (1.11) *large**
TS (AU)	8.4 ± 0.8	11.3 ± 0.6	11.0 ± 0.5	2.9 ± 1.0 (2.35) *very large****	0.2 ± 0.8 (0.26)
TDC (AU)	4.2 ± 1.2	7.9 ± 0.7	6.9 ± 0.7	3.7 ± 1.4 (1.76) *large****	1.0 ± 1.0 (0.94)
RPE (AU)	13.9 ± 1.0	16.5 ± 0.7	16.3 ± 0.6	2.6 ± 1.3 (1.79) *large***	0.2 ± 1.0 (0.19)
Thirst (AU)	4.4 ± 1.0	5.3 ± 0.6	4.1 ± 0.9	0.9 ± 1.2 (0.71)	1.2 ± 1.1 (0.85)
Sweat loss (kg)	0.7 ± 0.2	1.1 ± 0.1	1.1 ± 0.2	0.4 ± 0.2 (1.62) *large**	0.0 ± 0.2 (0.09)
Sweat [Na^+] (mmol/l)	71.1 ± 7.8	80.2 ± 9.3	71.0 ± 5.2	9.1 ± 11.2 (0.72)	9.2 ± 10.1 (0.81)
Time Trial	266 ± 16 s	335 ± 50 s	282 ± 13 w	66 ± 42 (1.76) *large***	-

Cohens d are qualitatively described in *italics* and significance is indicated as; *** $p < 0.001$, ** $p < 0.01$, $^{*}p < 0.05$. AU = arbitrary units

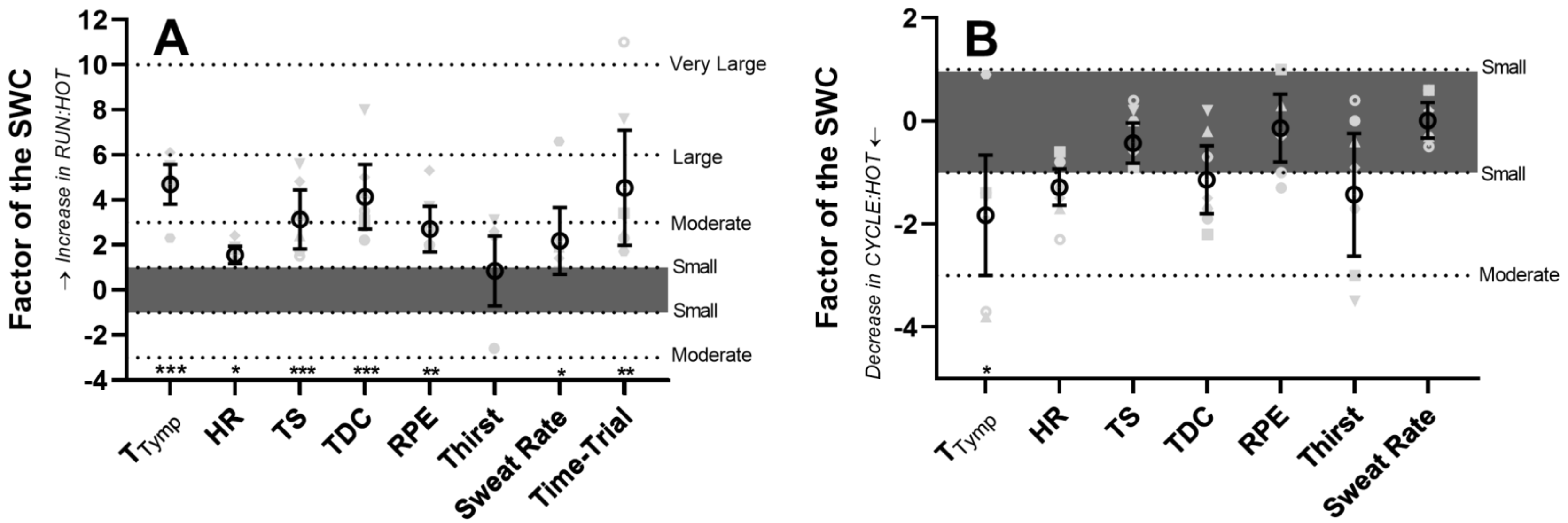

Figure 5-3: A-B: Changes (mean ± CL) in thermoregulatory markers including Tympanic temperature (T_{Tymp}), Heart Rate (HR), Thermal Sensation (TS), Thermal discomfort (TDC), Rate of Perceived Exertion (RPE), Thirst, Sweat Rate and Performance during different heat response testing protocols; Panel A = RUN:AMB - RUN:HOT; Panel B = RUN:HOT - CYCLE:HOT. Light grey symbols represent individual data points with each shape representing one individual. Changes are presented as the factor of the smallest worthwhile change (SWC; grey shaded area) and the magnitude of the effect is quantified as small (1x SWC), moderate (3x SWC), large (6x SWC) and very large (10x SWC). Quantitative chances are represented as *likely, **very likely, ***most likely chances of an increase/decrease.

5.5 Discussion

The current investigation was the first to our knowledge to investigate and compare the effects of acute heat stress during both on and off-feet exercise in an elite rugby sevens population. Acute heat stress resulted in large increases in physiological and perceptual thermal strain when compared to the same exercise stimulus performed in temperate conditions. Furthermore, it was shown that these increases in thermal strain were associated with a large performance decrement during a 1200 m running TT (Table 5-1; Figure 5-3A). When comparing running to cycling HRT's, moderate – large physiological differences were evident, whereas no clear effects on any variables associated with perceptual thermal heat stress were observed (Table 5-1; Figure 5-3B).

Previous research involving other international sevens teams indicate that T_{core} values during competition in the heat can regularly exceed 39.0 °C (Taylor et al., 2019b), values above which have been shown to impact high-intensity intermittent (Girard et al., 2015) and prolonged (Gonzalez-Alonso et al., 1999) exercise performance. Given that mean T_{Tymp} was >39.0 °C toward the end of the RUN:HOT condition (Figure 5-2), and increased cardiovascular demand was evident during exercise in the heat (Table 5-1; Figure 5-3A), it is most likely that that the performance decrement shown in the current study can be explained by physiological factors known to impact prolonged exercise. Furthermore, the increases in T_{Tymp} and cardiovascular demand are likely to have been exacerbated by mild dehydration (NBM loss was 39% greater in RUN:HOT compared to RUN:AMB) (Cheuvront & Kenefick, 2014) due to enhanced thermoregulatory demand for skin blood flow (Gonzalez-Alonso et al., 2008). These acute physiological responses act to drive the perceptual response (Tikuisis et al., 2002), as seen in the current study where TS, TDC and RPE exhibited large increases during RUN:HOT compared to RUN:AMB.

The current investigation indicates that a cycling-based HRT can be successful in reproducing the acute perceptual stress associated with a running-based HRT. Physiological differences were evident however, with higher T_{Tymp} and HR observed when running compared to cycling in the heat (Table 5-1; Figure 5-2 and Figure 5-3B). These findings concur with previous research that indicates higher $\dot{V}O_2$ and HR in treadmill vs. cycle ergometer exercise at submaximal and maximal intensities (Abrantes et al., 2012). Differences in activated muscle mass and posture contribute to differences in the cardiovascular and metabolic demands of running and cycling (Medelli et al., 1993). We postulate that the addition of full-body weighted exercise (down-ups) in the current study acted to blunt this difference seen in direct comparison studies. It has been shown that RPE can be higher within non-cycling experts during cycling vs. physiologically matched treadmill exercise (Abrantes et al., 2012; Green et al., 2003). However, during the current investigation there was no difference in RPE between running and cycling based HRT, despite increases in physiological stress during RUN:HOT, possibly indicating that the increase in physiological stress associated with running was offset by cycling being a non-specific secondary exercise mode for the athletes in the current investigation.

HRT are most often used pre and post an HA block to assess the resulting adaptations, with a rectal temperature of ~38.5 °C claimed to be the criterion to elicit heat adaptations during controlled hyperthermia HA protocols (Racinais et al., 2015). In the current study the 45 min cycling-based HRT elicited an end-exercise T_{Tymp} of 38.8 ± 0.4 °C (Figure 5-2). In turn, previous research has suggested that partial HA is possible after as little as four 30-45 min high-intensity cycle sessions in hot/humid conditions on consecutive days (Petersen et al., 2010). Together, these findings demonstrate that practitioners may be able to utilize short-duration high-intensity off-feet protocols, similar to the cycling-based HRT, to provide an adequate thermal stimulus to elicit heat adaptations (Périard et al., 2015; Taylor, 2014). This is useful for elite team sport practitioners, demonstrating the potential for traditional long-duration running-based heat training sessions to be replaced with sports-specific low impact alternatives. We also note that the thermal stimulus could be lengthened by the addition of pre- or post-session passive heat stress, which is most likely to reflect circumstances that are acceptable and practical to include within an elite team sports training schedule (Casadio et al., 2017; Zurawlew et al., 2018).

5.6 Practical applications

To our knowledge, the present investigation was the first to demonstrate the detrimental impact that acute heat stress can have on performance in non-heat acclimated international rugby sevens athletes. With many major rugby sevens events worldwide being held in thermally challenging environments, practitioners need to consider how they can integrate HA into their pre-competition schedule, without foregoing other training priorities. While the use of a cycling-based HRT can replicate the perceptual stress of a similar running test in the heat, giving the benefit of conserving running load for specific training, the physiological heat stress whilst running was greater. Practitioners working with running team sport athletes should be aware of this when designing and assessing HA protocols. When using cycling as an exercise heat stress, methods to exacerbate the thermal impulse could be considered, such as increasing exercise time/intensity or including pre/post passive heat.

5.7 Conclusion

Acute heat stress causes large increases in physiological and perceptual strain, resulting in detrimental performance outcomes in non-heat acclimated elite rugby sevens athletes. High-intensity running in the heat induces high physiological strain and additional mechanical load that may not be suitable for elite team-sport athletes, meanwhile, high-intensity cycling in the heat induces thermal strain sufficient to drive adaptation and can replicate the perceptual, but not the physiological stress associated with high-intensity running in the heat.

Chapter Six Practical application of a mixed active and passive heat acclimation protocol in elite male rugby sevens athletes

Fenemor, S. P., Driller, M. W., Gill, N., Mills, B., Casadio, J., & Beaven, C. M. (2022). Practical application of a mixed active and passive heat acclimation protocol in elite male Olympic team sport athletes. *Applied Physiology, Nutrition, and Metabolism*. Advance online publication. https://doi.org/10.1139/apnm-2022-0112

Prelude

Chapter Four identified that elite male rugby sevens athletes can exhibit significantly elevated T_c, approaching and above those associated with impaired repeated sprint performance and environmental heat illness symptoms, while Chapter Five identified that acute heat stress can be detrimental to time-trial performance in rugby sevens athletes. As such, Chapter Six endeavoured to use a practical, applied, training-integrated heat acclimation intervention to alleviate the physiological and perceptual stressors that collectively impair performance.

6.1 Abstract

To investigate effectiveness and retention of heat acclimation (HA) integrated within an elite rugby sevens team training program, 12 elite male rugby sevens athletes undertook 10-days of mixed active/passive HA across two-weeks of normal training. Physiological and performance variables were assessed using a sport specific, repeated high-intensity heat-response test Pre-HA; after five (Mid-HA) and 10 days (Post-HA); and 16-days post-HA (Decay). Resting, submaximal, and end-exercise core temperature were lower at Mid-HA (≤ -0.26 °C; *d* ≥-0.47), Post-HA (≤ -0.30 °C; *d* ≥-0.72), and Decay (≤ -0.29 °C; *d* ≥-0.56), compared to Pre-HA. Sweat rate was greater Post-HA compared to Pre-HA (0.3 ± 0.3 $L \cdot hr^{-1}$; *d* =0.63). Submaximal HR was lower at Mid (-9 ±4 bpm; *d* =-0.68) and Post-HA (-11 ± 4 bpm; *d* =-0.90) compared to Pre-HA. Mean and peak 6-s power output improved Mid-HA (83 ± 52 W; 112 ± 67 W; *d* ≥0.47) and Post-HA (125 ± 62 W; 172 ± 85 W; *d* ≥0.72) compared to Pre-HA. Improvements in HR and performance persisted at Decay (*d* ≥0.66). The initial five days of mixed-methods HA elicited many typical HA adaptations, with an additional five days eliciting further thermoregulatory, sudomotor, and performance improvements. Adaptations were well-retained after 16-days of normal training, without any further heat stimulus.

The trial was retrospectively registered with the Australian New Zealand Clinical Trials Registry (ACTRN12622000732785).

6.2 Introduction

Heat acclimation (HA) is regarded as the best countermeasure to minimise heat-induced physiological strain, lower the incidence of heat-illness, and improve athletic performance in the heat for team sport athletes (Racinais et al., 2015). The general premise of HA involves exposing athletes to a series of increases in core body temperature (T_c) over time (often referred to as thermal impulses) through either passive and active means (Taylor, 2014), with typical physiological adaptations including lowered resting and exercising T_c and heart rate, plasma volume expansion, and a higher exercise sweat rate (Périard et al., 2015). Together, these facilitate a reduction in measures of thermal perception and enhanced exercise performance/capacity in the heat (Tyler et al., 2016). The induction of these physiological adaptations is not uniform however, with ~75% of adaptations in heart rate, T_c, and plasma volume occurring within ~4 to 6 days (Garrett et al., 2009; Pandolf, 1998), while changes in peak sweat rate can take up to two-weeks of daily heat exposure (Daanen et al., 2018).

In recent times, a plethora of research concerning HA has emerged, largely due to the challenging environmental conditions that were expected at the Tokyo 2020 Olympic Games (Kakamu et al., 2017). In some contexts, this previous research is practically useful for prescribing HA strategies, however, the sustained nature of many of the interventions, along with non-elite populations, make the ecological validity difficult to interpret in an elite team sport context (Casadio et al., 2017). Previous literature clearly indicates the benefits of exercise-based HA; however, competing training priorities (e.g. sport-specific skills, strength training) and logistical/practical burdens (e.g. lack of access to controlled artificially hot environments) can prohibit such HA protocols from being feasible. As a result, passive methods of HA, such as hot water immersion (HWI) have been explored with encouraging results, particularly when used immediately post-exercise (Heathcote et al., 2018; McIntyre et al., 2021; Zurawlew et al., 2018). When a training facility has adequate HWI facilities nearby, passive HA protocols can represent a practical and physiologically beneficial HA strategy; however, sole use of passive exposures may not be as effective as active HA for the development of sport-specific adaptations or performance benefits (Daanen et al., 2018; Gibson et al., 2019a). As such, it has been proposed that combining active and passive exposures during a HA protocol may provide the best blend of meaningful physiological, perceptual and performance adaptations in an elite context, without compromising other training priorities (Casadio et al., 2017; Pryor et al., 2019a).

The thermal stimulus throughout a HA protocol must be progressively elevated to exceed an individual's threshold for adaptation (Taylor, 2014). There are many approaches to achieve this; including self-paced exercise, constant (set) work-rate exercise, passive heating, post-exercise passive heating, controlled hyperthermia, and controlled heart rate HA (Gibson et al., 2019a). Typically, isothermic protocols (i.e. controlled T_c; usually at ~ 38.5 °C) have been utilised in previous literature, as they allow greater workloads to be produced for a set T_c, as adaptation occurs (Garrett et al., 2012; Pethick et al., 2018). Although this approach allows experimental control, its practicality has been questioned in applied sport settings, due to the need to continuously monitor T_c, the need for progressively increased exercise intensities, and typically long exercise exposures (Gibson et al., 2019a). As such, the use of heart rate has been proposed to provide a feasible means for regulating HA intensity for elite athletes (Périard et al., 2015; Stephenson et al., 2019), with the notion being that as cardiovascular, thermoregulatory and haematological adaptations occur, greater work output will be possible at any given heart rate range, thus providing a progressive overload with respect to the thermal impulse (Gibson et al., 2019a). Furthermore, given that heart rate is a frequently used monitoring and assessment tool in elite sport, heart rate-controlled HA has the benefit of familiarity and ease of use in an applied sport setting. For further discussion of the significance of controlled and regulated physiological variables during heat adaptation, the reader is directed to the review of Taylor and colleagues (2020).

The retention of adaptations following the removal of heat stimulus is another important consideration for elite teams when preparing to compete in the heat. Adaptation retention is largely dependent on training status and the initial cumulative thermal impulse (factored by time, intensity, mode), with a higher training status and greater initial thermal impulse eliciting greater retention (Gibson et al., 2019a; Taylor, 2014). Much of the current evidence suggests that physiological, perceptual, and performance changes can be well-retained across the following ~14 days after the heat stimulus is removed (Daanen et al., 2018; Duvnjak-Zaknich et al., 2019); however, there is a paucity of evidence regarding HA adaptation retention in an elite team sport context.

Rugby sevens is often played in hot environmental conditions, and recent research has demonstrated the regular occurrence of high T_c (>39 °C) during international rugby sevens in hot/humid conditions (Fenemor et al., 2021; Taylor et al., 2019b); thus, the inclusion of HA when preparing for international rugby sevens tournaments in hot conditions is well-indicated. Consideration of the multiple factors influencing HA induction and retention, along with practical considerations for integration within an elite training schedule, creates complex questions regarding the optimal design of HA protocols. As a result, the purpose of the current study was to investigate the effectiveness of 10-days of mixed-methods HA, integrated within an elite rugby sevens teams training program. Furthermore, it was investigated whether any resulting physiological, perceptual and performance changes could be retained after 16 days of normal training, without any further heat stimulus. It was hypothesised that 10-days of a mixed active and passive HA protocol would confer physiological, perceptual, and performance benefits that would be well-retained after 16 days of normal training, without any further heat stimulus.

6.3 Methods

6.3.1 Participants

Data was collected from 12 male athletes (age 23 ± 2 y; body mass 94.7 ± 6.4 kg; height 187 ± 5 cm) from the same international rugby sevens team (current world champion and Olympic silver medallists). All participants provided informed consent prior to testing, and ethical approval for the study was obtained through the University of Waikato Human Research Ethics Committee (HREC2018#64) in the spirit of the Declaration of Helsinki. The trial was retrospectively registered with the Australian New Zealand Clinical Trials Registry (ACTRN12622000732785).

6.3.2 Design

All subjects undertook a 10-day HA protocol incorporated into two weeks of normal rugby sevens training in local springtime conditions (six rugby-specific sessions; four gym sessions; no training on weekends). Thermoregulatory, cardiovascular, and perceptual responses to heat stress were assessed using a specifically designed heat response test (HRT), intended to replicate the fixed and maximal intensity demands of a rugby sevens warm up and game (Ross et al., 2015a). In total, four HRT were performed: Pre-HA (before the commencement of HA); Mid-HA (after five days of HA); Post-HA (after 10 days of HA); Decay (16 days after the end of HA). All HRTs and active HA sessions were performed in an environmental chamber maintained at 35 °C, 80% relative humidity (RH), replicating a possible scenario at the Tokyo 2020 Olympic Games (Kakamu et al., 2017). Participants refrained from strenuous exercise in the 24-hr before each HRT, and were instructed to arrive to the HRT in a euhydrated state (not thirsty). All HRT's were performed at the same time of day (mornings) to account for circadian rhythms. During the HA protocol, all participants undertook a mixture of active (exercise) and passive (hot water immersion; HWI) heat exposures (see below for details). Participants were asked to undertake permissive dehydration (i.e. refrain from drinking if possible) during the HA sessions, as this has previously been shown to enhance responses to HA (Garrett et al., 2014). During the entire 10-day acclimation process, the total heat exposure for each participant was 7 h 45 min, noting that the Pre-HA and Mid-HA HRTs were considered part of the overall HA thermal stimulus. An overview of the HA timeline is shown in Figure 6-1.

Week	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**	**Heat exposure *(mins)***
1	Pre-HA HRT *45 min*	HA1 *40 min*	HWI1 *40 min*	HA2 *45 min*	HWI2 *40 min*	*No heat exposure*		*210*
2	Mid-HA HRT *45 min*	HA1 *40 min*	HWI1 *40 min*	HWI2 *40 min*	HA2 *45 min*	*No heat exposure*		*210*
3	Post-HA HRT *45 min*	*Normal training*						*45*
4	*Normal training*							***Total 465 mins***
5				Decay HRT *45 min*				

Figure 6-1: Overview of the mixed-methods heat acclimation timeline, including weekly mins of heat exposure. HRT = Heat Response Test; HA= Exercise-based heat acclimation session (1 and 2); HWI1 = Passive heat acclimation session involving 40 min hot-water immersion (40 ºC); HWI2 = the same protocol as HWI1, performed immediately after an on-field training session.

6.3.3 *Heat response test*

All HRTs were performed on a calibrated cycle ergometer (WattBike Ltd, Nottingham, UK) and consisted of a 24-min fixed intensity warm-up, followed by intermittent sprints with the same time structure as a rugby sevens game (2x 7-min halves, with a 2-min halftime break; as described below). The warm-up took the following structure; 7-min cycling at 2.0 W·kg^{-1} (submaximal); 1-min rest; 7-min cycling at 3.0 W·kg^{-1}; 1-min rest; and 3-min cycling at 2.0 W·kg^{-1} with submaximal accelerations during the final 6-s of each minute, followed by a 5-min rest. The repeated intermittent sprint (R-SPRINT) section consisted of 24-s cycling at 3.0 W·kg^{-1}, immediately followed by a 6-s maximal sprint and 40-s rest, repeated 12 times with a 2-min half-time break after interval 6. During rest periods, athletes were permitted to spin their legs (with minimal power output). A cycling power output of 3.0 W·kg^{-1} was chosen as this reflected the individual mean heart rate during maximal aerobic speed running during pilot testing. The design and content of the repeated interval protocol was chosen as it replicates game average high-intensity work: rest ratios [30 s: 40 s; (Ross et al., 2015a)] without the increased mechanical load associated with high-intensity running. Peak power output (PPO) and mean power output (MPO) during the 6-s maximal sprints were used as performance measures. Fatigue index percentage (Fatigue%) was also calculated for both PPO and MPO as shown in equation 1 (Glaister et al., 2008).

Equation 1: Calculation of Fatigue Index (Fatigue%) for Peak and Mean power output (PO)

$$Fatigue\% = \frac{sum\ of PO}{12(\max PO)}$$

Physiological and perceptual measures (as described below) were recorded during seated rest (resting), after each warm-up stage, and after every third interval of the intermittent sprint section. Where necessary, measurements were averaged to be used in the final analysis (i.e. warm-up and R-SPRINT).

6.3.4 *Active HA sessions*

All participants undertook two active HA sessions per week (four active heat sessions in total), with these sessions being performed within 15 minutes of an on-field training session. The first session (HA1) consisted of ten 2-min intervals performed on a cycle ergometer separated by 2-min rest. During each cycling interval, participants were instructed to rapidly elevate and maintain their heart rate to 85% of their measured maximum. Mean 2-min power output was recorded by a researcher. The second session (HA2) consisted of 10-min fixed intensity cycling (5-min at 2.0 $W \cdot kg^{-1}$; 5-min at 3.0 $W \cdot kg^{-1}$); six 500 m rowing intervals (Concept 2 Inc., Morrinsville, VT), at a target pace of 1-min 50-s per 500 m, separated by 2-min rest; followed by a 10-min cycling interval where participants were instructed to keep their heart rate at 85% of their measured maximum, with mean power output being recorded. The content of these active HA sessions was chosen for athlete familiarity, and practicality within a sevens squad. Specifically, HA1 (lower intensity) coincided with a high-intensity on-field training session, while HA2 (higher intensity) followed a low-intensity on-field training session.

6.3.5 *Hot water immersion (HWI) sessions*

All participants undertook four passive HWI sessions (two per week). HWI1 was performed without any prior exercise, as this coincided with a scheduled mid-week non-training day, while HWI2 was performed within 15 min of an on-field training session. All HWI were undertaken in an upright tub for 40 min in 40 °C water. Participants were instructed to stand, immersed to the top of the chest (including arms) for the first 25 min of each exposure, after which time they could elevate to the mammillary line, and bring their arms out of the water.

6.3.6 *Physiological measurements*

During all HRT's, T_c was measured using a rectal thermistor (U thermistor, Grant Instruments Ltd., Cambridge, United Kingdom), self-inserted to a depth of 10 cm beyond the anal sphincter. T_c was recorded at 1-min intervals on a portable data logger (2020 series data logger, Grant Instruments Ltd., Cambridge, United Kingdom) and averaged over each measurement period. Heart rate (HR; Polar H10, Polar Electro Oy, Kempele, Finland) was monitored throughout each HRT as well as during the active HA sessions to prescribe exercise intensity. To estimate sweat loss, towel-dried, nude body mass (NBM) was recorded to 0.1 kg using digital scales (Tanita HD-351, Tanita Health Equipment H.K. Limited) before and immediately after each HRT and each HA session, this value was adjusted for a standardised amount of ingested liquid during the HRT (640 mL). Sweat loss was converted to sweat rate ($L \cdot h^{-1}$), for subsequent analysis.

6.3.7 *Perceptual Measurements*

Rating of perceived exertion [RPE: 6-20 scale; (Borg, 1970)], thermal sensation [1-13 point scale; (Gagge et al., 1967)], thermal comfort [1-10-point scale; (Gagge et al., 1967)], and thirst sensation [Thirst: 1-9 point scale; (Riebe et al., 1997)] were collected at the same time points described above. Additionally, RPE, thermal sensation and thermal comfort were collected at the end of each HA session (RPE during active sessions only).

6.4 Statistical analysis

One-way repeated measures ANOVA was used to determine main effects for all variables between Pre-HA, Mid-HA, Post-HA, and Decay, along with interaction over time for all dependent measures using IBM SPSS Statistics for Windows, Version 26.0. Normality was assessed using the Shapiro-Wilk test at each time point and Mauchly's test was used to test that sphericity had not been violated. On occasions where sphericity had been violated, the Greenhouse-Geisser correction was used. Where there was a main effect, magnitudes between each measurement period were determined and expressed as both mean differences ± 90% confidence limits (CL) and standardised effect sizes (Cohen's *d*). If the 90% CL for Cohen's *d* overlapped positive and negative trivial (± 0.20) *d* values, the effect was deemed *unclear*; 90% CL were used due to the small sample size as suggested by Turner et al. (2021). Substantial clear effects were described using standard thresholds of < 0.20 *trivial*, 0.20 – 0.49 *small*, 0.50 – 0.79 *moderate*, and > 0.80 *large* (Cohen, 1988). A p-value of ≤ 0.05 was deemed to be statistically significant. The smallest worthwhile change (SWC) for rectal temperature (as depicted in

Figure 6-2) was determined from a recent meta-analysis (Tyler et al., 2016), while the SWC for all performance metrics (as depicted in Figure 6-3) was calculated as one third of the pre-test coefficient of variation (%) (Hopkins, 2004).

6.5 Results

Group mean (±SD) physiological and perceptual variables for each HRT are presented in Table 6-1; Both the raw mean (± 90% CL) and standardised mean differences for each comparison are presented in Table 6-2. Group mean (±SD) and standardised mean differences for power output, RPE, thermal sensation, thermal comfort, and sweat rate during each active and passive heat acclimation session are presented in Table 6-3. All comparisons were normally distributed, as assessed by Shapiro-Wilk's tests ($p > 0.05$).

6.5.1 Physiological measurements

The HA intervention elicited statistically significant changes in resting T_c [$F_{(2, 22)} = 12.158$, $p < 0.001$], submaximal T_c [$F_{(2, 22)} = 8.946$, $p = 0.001$] and end exercise T_c [$F_{(2, 22)} = 10.476$, $p = 0.001$] over time. Resting, submaximal and end exercise T_c were lower at Mid-HA (all $p < 0.05$; $d \geq -0.47$) and Post-HA compared to Pre-HA (all $p < 0.01$; $d \geq -0.72$), while there were no differences in resting, submaximal or end exercise T_c Post-HA compared to Mid-HA. At the Decay test, resting, submaximal and end exercise T_c were all lower, compared to Pre-HA (all $p < 0.01$; $d \geq -0.56$), while there were no significant differences in T_c between Decay and Post-HA. See

Figure 6-2, Table 6-1, and Table 6-2 for full descriptions of T_c change across each HRT.

The HA intervention elicited statistically significant changes in submaximal HR [$F_{(2, 22)} = 12.893$, $p < 0.001$] over time, however, there was no statistically significant changes in R-SPRINT HR. Submaximal HR was lower at Mid ($p = 0.003$; $d = -0.68$) and Post-HA ($p = 0.001$; $d = -0.90$) compared to Pre-HA, while submaximal HR was still lower at Decay compared to Pre-HA ($p = 0.001$; $d = -0.86$; see Table 6-1 and Table 6-2). Sweat rate was greater Post-HA compared to Pre-HA ($p = 0.05$; $d = 0.63$), and further increased at Decay compared to Post-HA ($p = 0.03$; $d = 0.37$; see Table 6-1 and Table 6-2).

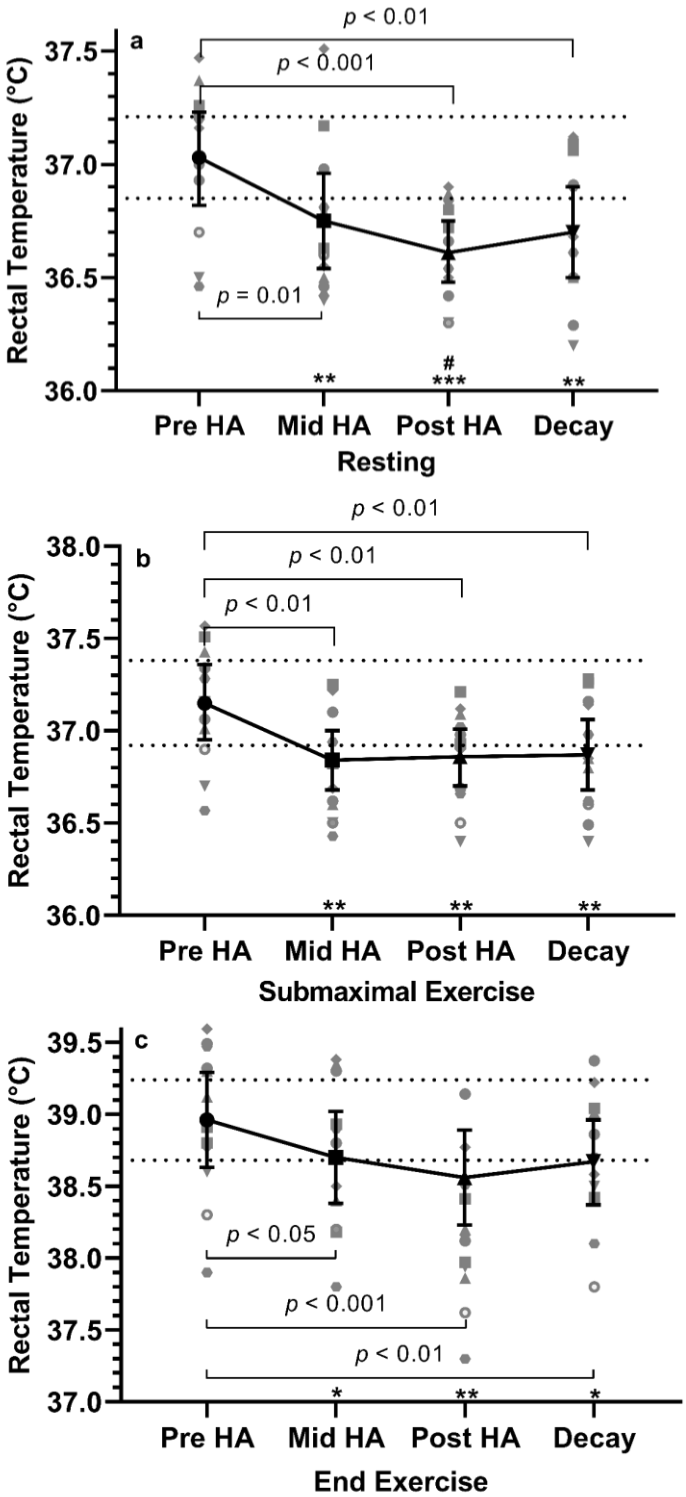

Figure 6-2: Resting (Figure 2a), Submaximal exercise (Figure 2b) and End exercise (Figure 2c) rectal temperature (°C) during Heat Response Tests Pre-HA, Mid-HA (5 days), Post-HA (10 days) and Decay (+16 days after Post-HA). The area between the dotted lines represents the smallest worthwhile change (± 0.3 °C of Pre-HA). Grey symbols represent individual data; black symbols and error bars represent mean ± 95% confidence limits. Where statistical significance occurred, it is indicated. Symbols above the x-axis represent standardised effect sizes (Cohen's *d*) for the following comparisons: * = compared to Pre-HA; # = compared to Mid-HA. The number of symbols represent the size of the effect; 1 = *small*, 2 = *moderate*, and 3 = *large*. HA = Heat Acclimation.

6.5.2 *Perceptual measurements*

The HA intervention did not lead to any statistically significant changes in submaximal and R-SPRINT thermal sensation or thermal comfort over time. The HA intervention elicited statistically significant changes in submaximal Thirst [$F_{(2, 22)}$ = 3.820, p = 0.038] and R-SPRINT Thirst [$F_{(2, 22)}$ = 9.177, p = 0.001] over time. There were some *small-moderate* changes in these perceptual measures between HRTs, as outlined in Table 6-1 and Table 6-2.

6.5.3 *Performance measurements*

MPO and PPO significantly increased Mid-HA compared to Pre-HA by 83 ± 52 W and 112 ± 67 W respectively (both p =0.01; d = 0.47 and 0.60). Compared to Pre-HA, MPO and PPO were significantly increased Post-HA by 125 ± 62 W and 172 ± 85 W (both p = 0.004; d = 0.72 and 0.80). This significant increase in MPO and PPO persisted at Decay compared to Pre-HA by 129 ± 58 W and 214 ± 81 W (p = 0.002 and 0.001; d = 0.66 and 0.90).

Compared to Pre-HA, both MPO and PPO Fatigue% decreased (improved) at Mid-HA by 13 ± 6% and 9 ± 4% and respectively (both p = 0.01; d = 1.25 and 0.80); at Post-HA by 14 ± 6% and 11 ± 6% and respectively (both p = 0.001; d = 1.37 and 1.14); and at Decay by 11 ± 3% and 8 ± 4% and respectively (p = 0.001 and 0.01; d = 0.96 and 0.67). All absolute mean (± 95% CL) performance data and standardised effects (Cohen's d) are presented in Figure 6-3.

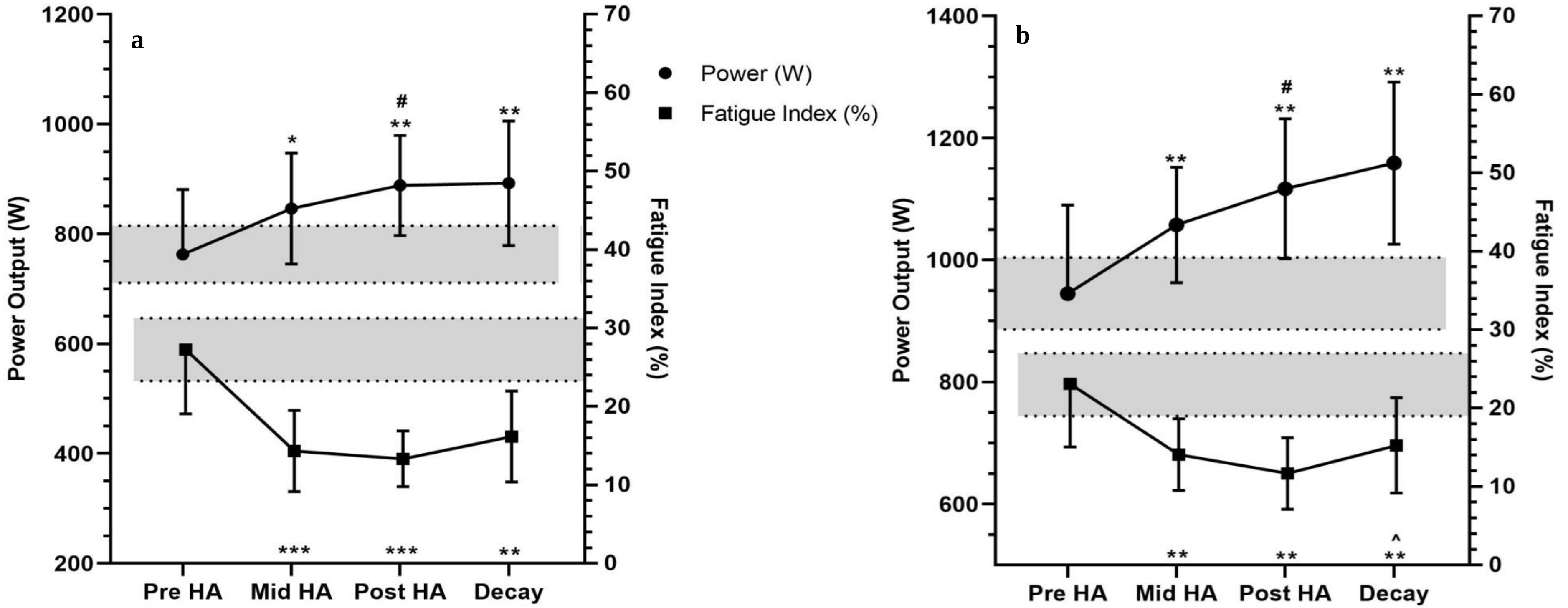

Figure 6-3: Mean (± 95% confidence limits) Power Output (W; closed circles) and Fatigue Index (%; closed squares) during Heat Response Tests Pre-HA, Mid-HA (5 days), Post-HA (10 days) and Decay (+16 days). Figure 3a represents average 6 s power; Figure 3b represents peak 6 s power. Shaded area represents the smallest worthwhile change for each variable, calculated as 1/3rd of the pre-test CV%. Symbols represent clear differences in standardised effect sizes (Cohen's *d*) for the following comparisons: * = compared to Pre-HA; # = compared to Mid-HA; ^ = compared to Post-HA. The number of symbols represent the size of the effect; 1 = small, 2 = moderate, and 3 = large; HA = Heat Acclimation.

Table 6-1: Mean ± SD for variables during heat response tests (HRT) pre-, mid-, post-, heat acclimation (HA) and +16 days (decay).

		Heat Response Test			
Variable	**Timepoint**	**Pre-HA**	**Mid-HA**	**Post-HA**	**Decay**
Core temperature (°C)	*Resting*	37.03 ± 0.33	36.75 ± 0.33*	36.61 ± 0.22***	36.70 ± 0.31**
	Sub-max	37.15 ± 0.32	36.84 ± 0.26**	36.86 ± 0.24**	36.87 ± 0.30**
	End Exercise	38.96 ± 0.52	38.70 ± 0.51*	38.56 ± 0.52***	38.67 ± 0.46**
Heart rate (bpm)	*Sub-max*	154 ± 12	144 ± 15*	142 ± 12***	141 ± 16***
	R-SPRINT	174 ± 11	172 ± 12	170 ± 9	173 ± 9
RPE (AU)	*Warm Up*	15.7 ± 1.5	15.1 ± 1.5	15.5 ± 1.3	15.4 ± 1.5
	R-SPRINT	19.2 ± 0.8	18.9 ± 0.7	19.0 ± 0.6	19.3 ± 0.7
Thermal sensation (AU)	*Warm Up*	10.8 ± 0.7	10.6 ± 0.9	10.9 ± 0.6	10.6 ± 0.9
	R-SPRINT	12.1 ± 0.6	11.9 ± 0.8	12.2 ± 0.7#	12.1 ± 0.8
Thermal comfort (AU)	*Warm Up*	6.6 ± 1.0	6.2 ± 1.5	6.3 ± 1.4	5.6 ± 1.5*^
	R-SPRINT	8.9 ± 0.9	8.6 ± 1.2	8.6 ± 1.4	8.7 ± 1.3
Thirst (AU)	*Warm Up*	4.1 ± 1.2	3.2 ± 1.6*	3.1 ± 1.8*	3.0 ± 1.4*
	R-SPRINT	6.0 ± 2.3	4.4 ± 2.3*	4.2 ± 2.7**	4.0 ± 2.3**
Sweat rate ($L \cdot hr^{-1}$)	*Mean*	1.9 ± 0.5	2.0 ± 0.5	2.2 ± 0.5*	2.3 ± 0.4**^
Peak blood [La^+] $mmol \cdot L^{-1}$	*Mean*	10.3 ± 3.1	10.5 ± 2.9	11.0 ± 3.1	10.0 ± 2.7

* = different to Pre; # = different to mid; ^ = different to post. The number of symbols represent the significance level; 1 = $p \leq 0.05$, 2 = $p \leq 0.01$, and 3 = $p \leq 0.001$; AU = Arbitrary Units; RPE = Rate of perceived exertion.

Table 6-2: Mean difference ± 90% confidence limits; (Cohen's *d*) for variables during heat response tests (HRT) pre-, mid-, post-, heat acclimation (HA) and +16 days (decay).

Variable	Timepoint	Mid - Pre	Post - Pre	Post - Mid	Decay - Post	Decay - Pre
Core temperature (°C)	*Resting*	-0.27 ± 0.17; (-0.78) ***moderate***	-0.41 ± 0.15; (-1.39) ***very large***	-0.14 ± 0.19 (-0.47) ***small***	0.08 ± 0.14 (0.29) *trivial*	-0.29 ± 0.16 (-0.71) ***moderate***
	Sub-max	-0.32 ± 0.17; (-1.03) ***large***	-0.30 ± 0.14; (-0.97) ***large***	0.02 ± 0.14 (0.08) *unclear*	0.01 ± 0.11 (0.04) *unclear*	-0.30 ± 0.15 (-0.87) ***large***
	End Exercise	-0.26 ± 0.16 (-0.47) ***small***	-0.40 ± 0.12; (-0.72) ***moderate***	-0.14 ± 0.16 (-0.26) *trivial*	0.11 ± 0.15 (0.20) *trivial*	-0.30 ± 0.17 (-0.56) ***moderate***
Heart rate (bpm)	*Sub-max*	-9 ± 4; (-0.68) ***moderate***	-11 ± 4; (-0.90) ***moderate***	-2 ± 5; (-0.12) *unclear*	-1 ± 4; (-0.12) *unclear*	-13 ± 5; (-0.86) ***moderate***
	R-SPRINT	-3 ± 3; (-0.22) *trivial*	-4 ± 4; (-0.38) *trivial*	-1 ± 4; (-0.12) *unclear*	3 ± 3; (0.34) *trivial*	-1 ± 3; (-0.08) *unclear*
RPE (AU)	*Warm Up*	-0.6 ± 0.5; (-0.34) ***small***	-0.2 ± 0.6; (-0.10) *unclear*	0.4 ± 0.6; (0.27) *trivial*	-0.1 ± 0.4; (-0.05) *unclear*	-0.2 ± 0.6; (-0.14) *unclear*
	R-SPRINT	-0.3 ± 0.4; (-0.31) *trivial*	-0.1 ± 0.4; (-0.17) *unclear*	-0.1 ± 0.3; (-0.18) *unclear*	0.2 ± 0.3; (0.28) *trivial*	-0.1 ± 0.4; (0.09) *unclear*
Thermal sensation (AU)	*Warm Up*	-0.2 ± 0.4; (-0.20) *unclear*	0.1 ± 0.3; (0.20) *unclear*	0.3 ± 0.4; (0.39) *trivial*	-0.3 ± 0.4; (-0.41) *trivial*	-0.2 ± 0.3; (-0.23) *trivial*
	R-SPRINT	-0.3 ± 0.2; (-0.33) ***small***	0.1 ± 0.2; (0.08) *unclear*	0.3 ± 0.1; (0.40) ***small***	-0.1 ± 0.2; (-0.08) *unclear*	0.0 ± 0.2; (-0.01) *unclear*
Thermal comfort (AU)	*Warm Up*	-0.4 ± 0.5; (-0.37) *trivial*	-0.3 ± 0.5; (-0.25) *trivial*	0.1 ± 0.4; (0.09) *unclear*	-0.7 ± 0.5; (-0.46) ***small***	-0.9 ± 0.7; (-0.74) ***moderate***
	R-SPRINT	-0.3 ± 0.3; (-0.27) *trivial*	-0.3 ± 0.4; (-0.26) *trivial*	0.0 ± 0.3; (-0.02) *unclear*	0.1 ± 0.4; (0.04) *unclear*	-0.2 ± 0.4; (-0.21) *trivial*
Thirst (AU)	*Warm Up*	-0.9 ± 0.7; (-0.62) ***moderate***	-0.9 ± 0.8; (-0.69) ***moderate***	-0.1 ± 0.3; (-0.10) *unclear*	-0.1 ± 0.4; (0.02) *unclear*	-1.1 ± 0.6; (-0.76) ***moderate***
	R-SPRINT	-1.6 ± 0.9; (-0.63) ***moderate***	-1.9 ± 1.1; (-0.75) ***moderate***	-0.2 ± 0.3; (-0.18) *unclear*	-0.2 ± 0.5; (-0.02) *unclear*	-2.0 ± 0.9; (-0.80) ***large***
Sweat rate ($L \cdot hr^{-1}$)	*Mean*	0.2 ± 0.2; (0.34) ***small***	0.3 ± 0.3; (0.63) ***moderate***	0.1 ± 0.3; (0.30) *trivial*	0.2 ± 0.2; (0.37) ***small***	0.4 ± 0.3; (1.00) ***large***
Peak blood [La^+] $mmol \cdot L^{-1}$	*Mean*	0.2 ± 1.2; (0.09) *unclear*	0.7 ± 1.5; (0.22) *unclear*	0.5 ± 1.2; (0.14) *unclear*	-1.0 ± 0.9; (-0.28) ***small***	-0.3 ± 1.6; (-0.03) *unclear*

Table 6-3: Mean ± SD power output (W) and thermoregulatory variables during exercise (active) and passive hot-water immersion (HWI) heat acclimation sessions on week one and week two.

		Cycling power output (W)	**RPE (AU)**	**Thermal sensation (AU)**	**Thermal comfort (AU)**	**Sweat rate ($L \cdot hr^{-1}$)**
Active session one	Week 1	211 ± 22	16.9 ± 1.2	10.3 ± 0.6	7.7 ± 0.9	2.6 ± 0.7
	Week 2	225 ± 26	17.2 ± 1.8	9.8 ± 0.8	7.5 ± 1.3	3.0 ± 0.9
	Cohen's d	*0.50* ***small***	*0.12 unclear*	*-0.53* ***small***	*-0.22 trivial*	*0.40* ***small***
Active session two	Week 1	100 ± 20	18.3 ± 1.3	12.1 ± 0.8	8.6 ± 1.0	2.0 ± 0.5
	Week 2	108 ± 18	17.8 ± 1.6	11.6 ± 1.0	8.3 ± 1.5	2.4 ± 0.7
	Cohen's d	*0.42* ***small***	*-0.31 trivial*	*-0.53* ***small***	*-0.22 trivial*	*0.49* ***small***
HWI session one	Week 1	-	-	12.7 ± 0.5	9.5 ± 0.6	1.7 ± 0.7
	Week 2	-	-	11.7 ± 0.9	7.8 ± 2.1	1.5 ± 0.5
	Cohen's d	-	-	*-1.29* ***large***	*-0.82* ***large***	*-0.23 trivial*
HWI session two	Week 1	-	-	10.8 ± 1.1	6.3 ± 1.5	1.2 ± 0.5
	Week 2	-	-	10.7 ± 1.1	7.3 ± 2.1	1.7 ± 0.6
	Cohen's d	-	-	*-0.14 trivial*	*0.41* ***small***	*0.64* ***moderate***

6.6 Discussion

In support of our hypothesis, five days of mixed-methods HA integrated into one-week of an elite team's training program elicited some typical physiological, perceptual, and performance adaptations, with an additional five days eliciting further improvements in T_c, sweat rate, and performance during an intermittent sprint HRT. Furthermore, most adaptations were retained after 16-days of normal training with no additional heat exposure, with only R-SPRINT HR and peak power Fatigue% showing small decay profiles.

The thermoregulatory adaptations described herein are in line with those expected, particularly changes in HR and T_c. In the current study, HR was decreased during submaximal exercise, possibly indicating an improvement in central hemodynamics in response to the demands of exercising in the heat (Gibson et al., 2019a; Périard et al., 2016). Similarly, resting (-0.42 °C), submaximal (-0.29 °C), and end exercise T_c (-0.40 °C) were reduced as a result of HA. These thermoregulatory adaptations represent functional physiological changes that are likely to contribute to increased exercise capacity, and consequently performance improvements (Lorenzo et al., 2010). Fenemor and colleagues (2021) recently demonstrated that T_c during warm-ups and games can regularly exceed 39 °C during an international rugby sevens tournament played in hot/humid conditions. Such elevated T_c are known to be detrimental for repeated-sprint performance (Beaven et al., 2018); hence, are indicative of the inclusion of HA when preparing for international rugby sevens tournaments in hot conditions. The performance improvements observed in MPO and PPO in the current study were well above the *a priori* SWC following five (12% and 14%, respectively) and ten (18% and 20%) days of HA, which is in line with performance improvements shown in previous research with similar HA durations [~7% following short term-HA; ~22%

following long-term HA (Tyler et al., 2016)]. It should be considered that the current study involved elite repeated high-intensity team sport athletes; hence, even though the athletes were familiar with this HRT, there may be some training effect present, due to the (relative) unfamiliarity of repeated high-intensity exercise on a cycle ergometer. This possible training effect may explain part of the large performance increase demonstrated in the current study. While absolute T_c values dropped at Mid, Post, and Decay, the mean changes in T_c between timepoints were similar in all trials. Furthermore, the demonstrated increases in MPO in the current study would increase metabolic heat production (which is the principal determinant of sweat rate) (Gagnon et al., 2013b); thus, confounding the interpretation of sweat rate changes, unless there was also a substantial change in mechanical efficiency. The similar changes in T_c despite higher rates of heat production (from greater MPO) are likely due to greater whole-body evaporative heat dissipation, resulting from a higher sweat rate and/or better evaporative efficiency (Cramer & Jay, 2015; Gagnon et al., 2013b). Given these likely (i.e., unmeasured) changes in whole-body evaporative heat dissipation, the magnitude of effect of the heat acclimation intervention may have been even larger than reported.

Moderate decreases in thirst sensation alongside *moderate* increases in sweat rate were shown as a result of HA. This relationship seems paradoxical, and may be a remnant of general perceptual acclimation, rather than of thirst adaptation *per se* (Akerman et al., 2016). Alternatively, the *moderate* reduction in thirst sensation could be related to permissive dehydration during HA sessions, resulting in athletes becoming familiar with consuming less fluid during exercise in hot environmental conditions. When extrapolated to a post-HA competition setting, practitioners should be aware that not proportionally increasing fluid replacement to match HA-induced increases in sweat rate will result in greater dehydration, particularly in humid environments (Périard et al., 2015).

The separate use of exercise-based and passive heat exposures has been extensively described and reviewed (Heathcote et al., 2018; Tyler et al., 2016). However, the use of a practical, combined approach that incorporates both active and passive heat exposures around concurrent training is currently confined to a case-study with a football referee (Ruddock et al., 2016), and one study in para- and able-bodied triathletes (Stephenson et al., 2019). In both cases, normal training was replaced with active HA sessions, which is not likely to be feasible in an elite team sport context. In turn, it has been recently demonstrated that heat re-acclimation using HWI is comparable to exercise-based methods (Gerrett et al., 2021). Together, these previous investigations indicate that a mixed active and passive HA protocol can be effective at stimulating thermoregulatory adaptations in endurance trained athletes and officials. While this approach is practical in an endurance context where normal trainings can be replaced by heat exposure sessions, within an elite team sport context, this is not practical due to concurrent on-field training that often focusses on technical and tactical training methods (Henderson et al., 2018; Marrier et al., 2018). Therefore, the current mixed-methods protocol represents a time-efficient stimulus for heat adaptation, presenting the first evidence of a realistic and ecologically valid solution to overcome the demands of elite training schedules.

The positive thermoregulatory adaptations from the current mixed-methods HA approach were achieved by prescribing a readily accessible and practical heart rate metric during exercise-based sessions. It has previously been suggested that using heart rate to regulate HA session intensity will provide a constant cardiovascular stimulus, and hence a constant thermoregulatory adaptation stimulus, across an acclimation block (Périard et al., 2015). However, this concept has received limited use in the literature, despite previous work showing a constant heart rate during isothermic HA sessions (Garrett et al., 2012; Pethick et al., 2018; Zurawlew et al., 2016). While isothermic HA protocols provide a progressively increasing thermal stimulus, such an approach may not be practical in an applied team sport environment due to the need for constant temperature monitoring. Therefore, the current study provides further evidence for the efficacy of using heart rate to regulate HA intensity in such a context. In the current study, athletes were able to maintain a constant relative thermal stimulus across each heat training session, exhibited via the lack of change in RPE and thermal comfort, and only small changes in TS between active HA sessions (Table 1). Furthermore, progression was indicated as athletes were able to produce greater external workload during active HA sessions on Week Two, which is in line with isothermic HA protocols, whereby greater workloads are produced across the course of a HA block.

The retention of thermoregulatory adaptations has significant implications for scheduling HA prior to competition, particularly in the current team sport context where specific training demands and travel often take precedence in the taper period (Casadio et al., 2017). In the current study, thermoregulatory changes between the Post-HA and Decay HRTs were either *unclear*, *trivial or small* (Tables 1 and 2), indicating that the adaptations resulting from HA were well-retained after 16-days of normal training, with no environmental heat stimulus. Indeed, the rates of decay within the current study are well within the bounds described in a previous meta-analysis (Daanen et al., 2018). This notion is further supported by only *trivial* changes in peak and average R-SPRINT power output at decay compared to Post-HA, combined with a *small* decrease in peak blood lactate, indicating little change in anaerobic capacity across the decay period. The increased sweat rate described after 16-days with no heat stimulus in the current study is an example of a morphological change with a longer time course than other physiological and cardiovascular adaptations (Périard et al., 2016; Sato et al., 1990). The initial magnitude of adaptation is likely a result of a combination of the high baseline training status of the population, the duration and type of activities within the HA, and the progressive overload approach (i.e. controlled HR) contributing to a sufficiently strong cumulative thermal impulse (Daanen et al., 2018; Taylor, 2014). In turn, the maintenance of high levels of physical activity [i.e. normal training weeks, characteristic of an international elite rugby sevens team (Marrier et al., 2018)] in the post-HA period likely contributed to the favourable adaptation retention shown in the current study (Gibson et al., 2019a).

6.7 Practical applications

The current study is the first to demonstrate the efficacy of a practical mixed active/ passive, heart-rate controlled HA protocol, integrated into an elite teams' training program. These findings are of particular interest to practitioners who have limited access to hot environments pre-competition. Furthermore, the described HA framework is generalisable to other team sports, and/ or sports that include similar weekly training models. In turn, similar HA protocols could facilitate readiness for deployment to hot climates in military personnel (Ashworth et al., 2020). Given that the athletes in the current study predominantly undertake repeated high-intensity running exercise as part of their normal training, there may have been some training effect resulting from the repeated high-intensity cycle ergometer exercise protocol. The ecological validity and high calibre of athletes are strengths of the current study; however, research in such a setting precludes the use of a control group engaging in thermoneutral exercise. Nonetheless, due to the calibre of athletes involved it is unlikely that any meaningful non-HA related adaptation occurred during this time (Lorenzo et al., 2010). Future research should test practical re-acclimation protocols 3-4 weeks after a similar HA protocol, giving further information to practitioners to support HA periodisation within a pre-competition schedule.

6.8 Conclusion

The current study provided initial evidence for the efficacy of a practical, and ecologically valid, mixed-methods HA protocol within an elite team's training program. While the integration of one week of such an HA protocol elicited many typical physiological, perceptual and performance adaptations, an additional week elicited further thermoregulatory, sudomotor and performance improvements. Furthermore, these adaptations were well-retained after 16-days with no additional environmental heat exposure. These novel findings have distinct implications for practitioners aiming to schedule HA into the pre-competition period.

Chapter Seven Heating up to keep cool: Benefits and persistence of a practical heat acclimation in an elite female rugby sevens team

Fenemor, S. P., Driller, M. W., Gill, N. D., Anderson, B., Casadio, J. R., Sims, S. T., & Beaven, C. M. (2022). Heating up to keep cool: Benefits and persistence of a practical heat acclimation in an elite female rugby sevens team. *International Journal of Sport Physiology and Perfornance*. In review

Prelude

Chapter Six demonstrated the utility of a practical, applied, training-integrated heat acclimation intervention. Chapter Seven endeavoured to build upon the findings of Chapter Six by applying a similar, yet more passive, heat acclimation approach with elite female rugby sevens athletes.

7.1 Abstract

Though recommendations for effective heat acclimation (HA) strategies for many circumstances exist, best-practice HA protocols specific to elite female team sport athletes are yet to be established. Therefore, we aimed to investigate the effectiveness and retention of a passive HA protocol, integrated within an elite female rugby sevens team training program.

Twelve elite female rugby sevens athletes undertook 10-days of passive HA across two-training weeks. Tympanic temperature (T_{Tymp}), sweat loss, heart rate (HR), and repeated 6-s cycling sprint performance were assessed using a sport-specific heat response test Pre-HA; after three days (Mid-HA); after 10 days (Post-HA); and 15-days post-HA (Decay).

Compared to Pre-HA, submaximal T_{Tymp} was lower Mid-HA and Post-HA (both by -0.2 ±0.1 °C; $d \geq 0.71$), while resting T_{Tymp} was lower Post-HA (by -0.3 ±0.1 °C; $d = 0.81$) There were no differences in T_{Tymp} at Decay compared to Pre-HA, nor were there any differences in HR or sweat loss at any timepoints. Mean peak 6-s power output improved Mid-HA and Post-HA (76 ±36 W; 75 ±34 W, respectively; $d \geq 0.45$) compared to Pre-HA. This performance improvement persisted at Decay by (65 ± 45 W; $d = 0.41$).

Ten days of passive HA can elicit some thermoregulatory and performance benefits when integrated into a training program in elite female team sport athletes. However, such a protocol does not provide a sufficient thermal impulse for thermoregulatory adaptations to be retained after 15-days with no further heat stimulus.

7.2 Introduction

Heat acclimation (HA) can elicit physiological adaptations such as lowered core body temperature (T_c), reduced resting and exercising heart rate, plasma volume expansion, and a higher exercise sweat rate (Gibson et al., 2019a; Périard et al., 2021). These adaptations facilitate a reduction in perceptual stress and enhanced exercise performance / capacity in the heat (Tyler et al., 2016). However, for highly-trained team sport athletes, HA may not be a high priority as they may be considered partially acclimated due to their underlying training status (Taylor et al., 2020), or competing training priorities prohibit exercise-based HA protocols being feasible. Furthermore, the lack of data specific to an elite female athlete population means that best-practice HA for female athletes remains in question (Hutchins et al., 2021; Wickham et al., 2021).

Females typically have an increased surface area-to-mass ratio, and increased sweating efficiency compared to males (Baker et al., 2020); however, sweating capacity, and hence evaporative heat loss capacity, is lower in females compared to males for a given amount of metabolic heat generation (Gagnon et al., 2013a; Gagnon & Kenny, 2011). These disparities in thermal stress are likely responsible for the longer general temporal pattern of adaptation described in females compared to males (Kirby et al., 2019; Mee et al., 2015) and have distinct implications for the structure of female specific HA protocols. For example, in controlled-hyperthermia HA protocols the T_c is typically clamped to 38.5 °C, regardless of sex, meaning the absolute thermal stress to the body may not be equal between sexes (Wickham et al., 2021).

When investigating sex differences in the physiological adaptations to HA, hormonal fluctuations associated with the menstrual cycle and/or oral contraceptive use can alter thermoregulatory responses and confound findings amongst females (Baker et al., 2020). Menstrual cycle phase and oral contraceptive use do not seem to impact thermoregulatory variables such as metabolic heat production, heat loss, or thermoeffector sensitivity during fixed or self-paced exercise in the heat (Notley et al., 2019). However, increases in progesterone during the luteal phase has been shown to increase the T_c setpoint by ~0.3 to 0.5 °C, which is mimicked in the active pill phase, and continues into the placebo phase during hormonal contraceptive use (Baker et al., 2001).

While the literature to date provides much needed insight into possible female specific HA protocols, the practicalities of including such protocols in an elite team sport environment remains challenging. Given that HA normally takes place in the pre-competition period, competing training priorities and logistical / practical burdens are likely to prohibit such controlled, sustained, and high-intensity exercise-based HA sessions being included at such a time (Casadio et al., 2017; Gibson et al., 2019a). These competing priorities are in part, why the emergence of passive methods of HA (such as sauna bathing or hot-water immersion) have been explored. Such methods give practitioners and athletes the ability to save mechanical load for specific training modalities, and have been shown to be particularly effective when performed immediately after a temperate training session (Heathcote et al., 2018; McIntyre et al., 2021; Zurawlew et al., 2018; Zurawlew et al., 2016). Indeed, hot-water immersion exposes individuals to a large uncompensable thermal stimulus (Cheung et al., 2000), and exposure to high skin temperatures has been shown to accelerate heat acclimation adaptation in females (Mee et al., 2018; Regan et al., 1996).

The retention of thermoregulatory adaptations is an important consideration for elite teams when preparing to compete in the heat. There is some suggestion that physiological, perceptual, and performance changes can be well-retained across the following ~14 days after a heat stimulus is removed (Daanen et al., 2018; Duvnjak-Zaknich et al., 2019; Pryor et al., 2019a). However, these suggestions are based on research involving HA protocols that may not be acceptable in an elite setting, along with being primarily performed in male and/ or endurance populations.

Integrating practical HA protocols within an elite team sport training schedule is an important consideration for practitioners when preparing to compete in hot environments. Therefore, the aims of the current study were to investigate the physiological, perceptual, and performance adaptations resulting from a 10-day (primarily) passive heat acclimation protocol integrated into an elite female team sport training program. Furthermore, it was investigated whether any resulting adaptations could be retained after 15 days without any further heat stimulus.

7.3 Methods

7.3.1 Subjects

Data were collected from 12 female athletes from the same world-champion and Olympic gold medal winning international rugby sevens team. Menstrual cycle status was recorded using a self-reported questionnaire (see **Table 7-1** for participant details). Of the naturally cycling, all four participants indicated that they were in days 15-28 of their menstrual cycle (luteal phase; see **Table 7-1**). All participants provided informed consent prior to testing, and ethical approval for the study was obtained through the University of Waikato Human Research Ethics Committee (HREC2018#64).

Table 7-1: Participant characteristics and contraceptive type use

Contraceptive type	**Participants**	**Day of menstrual cycle***	**Age (y)**	**Body mass (kg)**	**Height (cm)**
Natural	4	15, 20, 22, 25	22 ± 3	73.1 ± 7.3	168.3 ± 3.2
IUD	2	Not reported			
OCP	6	Not reported	23 ± 3	71.6 ± 6.6	168.8 ± 2.3
Mean	**12**	**-**	**22 ± 3**	**72.4 ± 7.3**	**168.6 ± 2.3**

IUD = intrauterine device; OCP = oral contraceptive pill

* reported at the Pre-HA HST

7.3.2 Design

All subjects undertook a 10-day HA protocol during two weeks of normal rugby sevens training. Thermoregulatory, cardiovascular, and perceptual responses to heat stress were assessed before, during, and after a specifically designed heat stress test (HST), intended to replicate the fixed intensity demands of a rugby sevens warm-up and maximal intensity of a rugby sevens game. In total, four HST were performed: Pre-HA (before the commencement of HA); Mid-HA (after 3 days of HA); Post-HA (after 10 days of HA); Decay (15 days after the end of HA). All HSTs were performed in an environmental chamber set at 35 °C, 80% RH, replicating a possible scenario expected at the Tokyo 2020 Olympic Games (Kakamu et al., 2017). Participants performed all testing sessions at the same time of day to account for circadian rhythms (Reilly & Brooks, 1986) and weekly training schedules. During the HA protocol, all participants undertook post-exercise sauna and hot water immersion (HWI) heat exposures (see below for details); whereas the pre- and mid-HA HST's functioned as exercise-based HA sessions. Participants were instructed to refrain from fluid consumption as much as could be tolerated during HA sessions (i.e., permissive dehydration) to induce the added stressor of dehydration (Akerman et al., 2016; Garrett et al., 2014). A schematic overview of the HA protocol is shown in Figure 7-1.

Week	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1					Pre-HST	*No heat exposure*	HWI
2	Post-ex-sauna	Post-ex-sauna	Mid-HST	HWI	Post-ex-sauna	HWI	*No heat exposure*
3	HWI	Post-ex-sauna	Post-HST	*No heat exposure*			
4	*No heat exposure*						
5	*No heat exposure*				Decay-HST		

Figure 7-1: Overview of the heat acclimation timeline. HST = Heat Response Test; HWI = passive heat acclimation session involving ~45 min hot-water immersion in ~40 °C water; Post-ex sauna = passive heat acclimation session involving 45-min passive rest in an environmental chamber set at 40 °C and 80 % RH.

7.3.3 *Heat response test*

All HST's were performed on a calibrated cycle ergometer (WattBike Ltd, Nottingham, UK) and consisted of a 24-min fixed intensity warm-up, followed by intermittent sprints with the same time structure as a rugby sevens game. In brief, the warm-up took the following structure; 7-min cycling at 2.0 W·kg^{-1} (submaximal); 1-min rest; 7-min cycling at 3.0 W·kg^{-1}; 1-min rest; and 3-min cycling at 2.0 W·kg^{-1} with submaximal accelerations during the final 6-s of each minute, followed by a 5-min rest. The repeated intermittent sprint (R-SPRINT) section consisted of 24-s cycling at 3.0 W·kg^{-1}, immediately followed by a 6-s maximal sprint and 40-s rest, repeated 12 times with a 2-min half-time break after interval 6. A power output of 3.0 W·kg^{-1} was chosen as this reflected individual mean heart rate during maximal aerobic speed running during pilot testing. Peak power output (PPO) and mean power output (MPO) during the 6-s maximal sprints were used as performance measures. Fatigue index percentage (FATIGUE%) was also calculated for both PPO and MPO by dividing the sum of the power outputs by the extrapolated hypothetical maximum power output (maximum power output multiplied by 12; equation 1). Physiological and perceptual measures (as described below) were taken during seated rest (resting), after each warm-up stage, and after every third interval of the intermittent sprint section, where appropriate measurements were averaged to be used in the final analysis (i.e. warm-up and R-SPRINT).

Equation 2: Calculation of Fatigue Index (FATIGUE%) for Peak and Maximal power output (PO)

$$FATIGUE\% = \frac{sum\ of PO}{12(\max PO)}$$

7.3.4 Post-exercise sauna sessions

All participants undertook four post-exercise sauna heat acclimation sessions, with these sessions being performed within 15-min of the end of an on-field training session. These sessions consisted of passive rest in an environmental chamber set at 40 °C and 80 % RH, in the following format (10-min standing; 15-min sitting undertaking game-specific analysis; 10-min sitting undertaking quiet reflection; 10-min standing).

7.3.5 *Hot water immersion (HWI) sessions*

All participants undertook four self-directed HWI sessions. These sessions were undertaken on non-training days, away from the teams normal training base. Participants were asked to spend 45 min immersed in 40 °C water, with the first 25 min submerged to the top of chest with arms also submerged. Participants were encouraged to remain fully immersed for the remaining 20 min, however, they could be submerged to the stomach if *very uncomfortable* (≥ 8 on TC scale; (Gagge et al., 1967)). It was instructed that one ≤ 3-min break could be taken, providing that there was no cold stimulus during that time (i.e., cold shower). Participants were given a portable temperature monitor (RS PRO TA298, RS Components Ltd, Auckland, New Zealand) and asked to record water temperature, along with total heat exposure time and session thermal sensation and thermal comfort.

7.3.6 *Physiological measurements*

During all HST's, tympanic temperature was measured using a validated device (Fenemor et al., 2020) (T_{Tymp}; Braun ThermoScan® 7 IRT6520, Braun GmbH, Kronberg, Germany). T_{Tymp} measurements were averaged to produce a value corresponding to each measurement period as described above. Heart rate (HR; Polar H10, Polar Electro Oy, Kempele, Finland) were sampled at the measurement periods described above. To estimate sweat loss, towel-dried, nude body mass (NBM) was recorded to 0.1 kg using digital scales (Tanita HD-351, Tanita Health Equipment H.K. Limited) before and immediately after each HST session, this value was adjusted for a standardised amount of ingested liquid during the HST (640 mL).

7.3.7 *Perceptual measurements*

Rating of perceived exertion (RPE; 6-20 scale) (Borg, 1970), thermal sensation (1-13 point scale) (Gagge et al., 1967), thermal comfort (1-10 point scale) (Gagge et al., 1967) and thirst sensation (Thirst; 1-9 point scale) (Riebe et al., 1997) were collected at the same time points described above for physiological measurements during the HST's. Thermal sensation and thermal comfort were collected at the end of each HA session.

7.4 Statistical analysis

Data was initially grouped as; natural menstrual cycle and IUD (Natural + IUD) vs. OCP groups as it is known that oral contraceptives down-regulate ovarian function, and the exogenous hormones create a stable hormone profile across the weeks of use (Chidi-Ogbolu & Baar, 2018). An independent-samples t-test was run to determine whether differences existed between the Natural + IUD and OCP groups in any of the measured variables with significance set at an alpha level of 0.05. Data from the Natural + IUD and OCP groups were pooled where appropriate, and one-way repeated measures ANOVA were used to determine main effects for all variables between Pre-HA, Mid-HA, Post-HA, and Decay, along with interaction over time for all dependent measures. Normality was assessed using the Shapiro-Wilk test at each time point and Mauchly's test was used to test that sphericity had not been violated. On occasions where sphericity had been violated, the Greenhouse-Geisser correction was applied. Where a main effect was identified, effect magnitudes were determined and expressed as both mean differences ± 90% confidence limits (CL) and standardised effect sizes (Cohen's *d*) sizes. If the 90% CL for Cohen's *d* overlapped positive and negative trivial (± 0.20) *d* values, the effect was deemed unclear. These effects were described using standard thresholds of < 0.20 *trivial*, 0.21 – 0.50 *small*, 0.51 – 0.80 *moderate*, 0.81 – 1.20 *large*, and > 1.20 *very large* (Cohen, 1988). The smallest worthwhile change (SWC) for rectal temperature (as depicted in Figure 7-2) was determined from a recent meta-analysis (Tyler et al., 2016), while the SWC for all performance metrics (as depicted in Figure 7-3) was calculated as one third of the pre-test CV% (Hopkins, 2004).

7.5 Results

During the entire 10-day acclimation process, the mean total heat exposure for each participant was 381 ± 23 min (HST: 90 min; sauna: 180 min; HWI: 115 ± 22 min). There were no significant differences in T_{Tymp}, RPE, thermal sensation, thermal comfort, and thirst between Natural + IUD and OCP at any timepoints across any of the HSTs. Peak HR was greater in the OCP group at pre (by 14 ± 9 bpm; p = 0.013), mid (by 14 ± 7 bpm; p = 0.001) and post (by 13 ± 8 bpm; p = 0.004) HSTs. Combined group mean (±SD) physiological and perceptual variables for each HST are presented in Table 7-2. Both the raw mean (± 90% CL) and standardised mean differences for each comparison are presented in Table 7-3.

Table 7-2: Mean ± SD for variables during heat response tests (HST) pre-, mid-, post-, heat acclimation (HA) and +15 days (decay). * = different to Pre; # = different to mid; ^ = different to post. The number of symbols represent the significance level; 1 = $p \leq 0.05$, 2 = $p \leq 0.01$, and 3 = $p \leq 0.001$

		Heat Response Test			
Variable	**Time**	**Pre-HA**	**Mid-HA**	**Post-HA**	**Decay**
Tympanic Temperature (°C)	*Resting*	37.3 ± 0.3	37.2 ± 0.3	37.0 ± 0.4***#	37.2 ± 0.2
	Sub-max	37.7 ± 0.2	37.6 ± 0.2*	37.5 ± 0.3**	37.5 ± 0.2
	End Exercise	38.6 ± 0.5	38.4 ± 0.4	38.6 ± 0.4	38.8 ± 0.4
Heart Rate (bpm)	*Sub-max*	151 ± 12	152 ± 6	149 ± 8#	151 ± 7
	R-SPRINT	171 ± 9	169 ± 8*	171 ± 7	171 ± 8
RPE (AU)	*Warm-up*	13.3 ± 0.9	13.9 ± 1.0*	14.8 ± 1.2**#	14.3 ± 0.7**
	R-SPRINT	16.1 ± 1.0	16.3 ± 1.1	17.1 ± 1.2*#	16.8 ± 1.4
Thermal Sensation (AU)	*Warm-up*	9.4 ± 1.2	9.4 ± 1.1	9.9 ± 0.4	9.7 ± 0.6
	R-SPRINT	9.7 ± 0.7	9.3 ± 0.8	10.2 ± 0.8##	9.8 ± 0.5
Thermal Comfort (AU)	*Warm-up*	5.0 ± 1.6	4.4 ± 1.3*	4.5 ± 1.3*	4.5 ± 1.4
	R-SPRINT	6.0 ± 1.6	5.4 ± 1.6*	5.7 ± 1.5	6.0 ± 1.5
Thirst (AU)	*Warm-up*	4.3 ± 1.5	4.1 ± 1.7	4.2 ± 1.2	4.2 ± 1.1
	R-SPRINT	5.7 ± 1.7	5.6 ± 2.0	5.5 ± 1.5	5.7 ± 1.5
Sweat Loss (kg)	*Mean*	1.3 ± 0.4	1.3 ± 0.4	1.3 ± 0.3	1.4 ± 0.4

RPE = Rate of perceived exertion; AU = Arbitrary Units

Table 7-3: Mean difference ± 90% confidence limits; (Cohen's *d*) for variables during heat response tests (HST) pre-, mid-, post-, heat acclimation and +15 days (decay).

Variable	Time	Mid - Pre	Post - Pre	Post - Mid	Decay - Post	Decay - Pre
Tympanic Temperature (°C)	*Resting*	-0.1 ± 0.1; (-0.34) *unclear*	-0.3 ± 0.1; (-0.81) ***large***	-0.2 ± 0.1 (-0.53) *moderate*	0.2 ± 0.2 (0.54) *unclear*	-0.1 ± 0.2 (-0.35) *unclear*
	Sub-max	-0.2 ± 0.1; (-0.71) ***moderate***	-0.3 ± 0.1; (-0.95) ***large***	-0.1 ± 0.1 (0.36) *unclear*	0.1 ± 0.2 (0.26) *unclear*	-0.2 ± 0.2 (-0.81) *large*
	End Exercise	-0.2 ± 0.2 (-0.44) *small*	-0.1 ± 0.3; (-0.12) *unclear*	0.2 ± 0.3 (0.33) *unclear*	0.2 ± 0.2 (0.46) *unclear*	-0.1 ± 0.3 (-0.32) *unclear*
Heart Rate (bpm)	*Sub-max*	1 ± 6; (-0.04) *unclear*	-2 ± 7; (-0.22) *unclear*	-3 ± 2; (-0.38) *small*	2 ± 5; (0.26) *unclear*	0 ± 5; (-0.03) *unclear*
	R-SPRINT	-2 ± 2; (-0.28) *trivial*	0 ± 4; (-0.38) *unclear*	3 ± 3; (-0.12) *unclear*	0 ± 2; (-0.02) *unclear*	0 ± 3; (-0.00) *unclear*
RPE (AU)	*Warm-up*	0.6 ± 0.5; (0.58) *moderate*	1.4 ± 0.7; (1.24) ***large***	0.8 ± 0.5; (0.67) ***moderate***	-0.4 ± 0.6; (-0.42) *unclear*	1.0 ± 0.4; (1.14) ***large***
	R-SPRINT	0.2 ± 0.7; (0.19) *unclear*	1.0 ± 0.8; (0.81) ***large***	0.8 ± 0.6; (0.62) *moderate*	-0.3 ± 0.4; (-0.23) *unclear*	0.6 ± 0.8; (0.49) *unclear*
Thermal Sensation (AU)	*Warm-up*	0.1 ± 0.4; (0.05) *unclear*	0.5 ± 0.5; (0.51) *unclear*	0.4 ± 0.5; (0.51) *unclear*	-0.2 ± 0.2; (-0.29) *unclear*	0.3 ± 0.5; (0.32) *unclear*
	R-SPRINT	-0.4 ± 0.4; (-0.45) *unclear*	0.5 ± 0.7; (0.50) *unclear*	0.9 ± 0.5; (1.01) ***large***	-0.4 ± 0.6; (-0.55) *unclear*	0.1 ± 0.5; (0.09) *unclear*
Thermal Comfort (AU)	*Warm-up*	-0.6 ± 0.4; (-0.40) ***small***	-0.5 ± 0.4; (-0.34) *trivial*	0.1 ± 0.4; (0.08) *unclear*	0.0 ± 0.5; (0.00) *unclear*	-0.5 ± 0.5; (-0.32) *unclear*
	R-SPRINT	-0.6 ± 0.5; (-0.32) *trivial*	-0.3 ± 0.5; (-0.17) *unclear*	0.3 ± 0.6; (0.16) *unclear*	0.3 ± 0.5; (0.18) *unclear*	0.0 ± 0.6; (0.00) *unclear*
Thirst (AU)	*Warm-up*	-0.2 ± 0.4; (-0.11) *unclear*	-0.1 ± 0.7; (-0.10) *unclear*	0.1 ± 0.6; (0.03) *unclear*	0.0 ± 0.3; (0.02) *unclear*	-0.1 ± 0.6; (-0.08) *unclear*
	R-SPRINT	-0.1 ± 0.4; (-0.07) *unclear*	-0.2 ± 0.6; (-0.12) *unclear*	-0.1 ± 0.6; (-0.03) *unclear*	0.2 ± 0.6; (0.10) *unclear*	0.0 ± 0.7; (-0.02) *unclear*
Sweat Loss (kg)	*Mean*	0.0 ± 0.1; (0.10) *unclear*	0.1 ± 0.1; (0.19) *unclear*	0.0 ± 0.1; (0.08) *unclear*	0.0 ± 0.2; (0.08) *unclear*	0.1 ± 0.1; (0.13) *unclear*

RPE = Rate of perceived exertion; AU = Arbitrary Units

7.5.1 *Physiological measurements*

The HA intervention elicited statistically significant changes in resting T_{Tymp} [$F_{(2, 22)} = 21.015$, $p < 0.001$], and submaximal T_{Tymp} [$F_{(2, 22)} = 7.557$, $p < 0.01$] over time; while there was no differences in end exercise T_{Tymp}. Submaximal T_{Tymp} was lower at Mid-HA compared to Pre-HA (p < 0.05; d = -0.71); while resting and submaximal T_{Tymp} was lower at Post-HA compared to Pre-HA (both p < 0.01; $d \geq -0.81$). There were no differences in resting, submaximal or end exercise T_{Tymp} at Decay compared to Pre-HA. See Figure 7-2, Table 7-2, and Table 7-3 for full descriptions of T_{Tymp} change across each HST. The HA intervention elicited no statistically significant changes in submaximal or R-SPRINT HR or sweat loss over time; see Table 7-2 and Table 7-3.

7.5.2 *Perceptual measurements*

The HA intervention did not lead to any statistically significant changes in submaximal thermal sensation over time; however, statistically significant changes in R-SPRINT thermal sensation [$F_{(2, 22)} = 4.180$, p = 0.05] were evident. The HA intervention elicited statistically significant changes in submaximal thermal comfort [$F_{(2, 22)}$ = 5.896, p = 0.01], but not R-SPRINT thermal comfort over time. The HA intervention did not lead to any statistically significant changes in submaximal and R-SPRINT Thirst over time. There were some *small* changes in these perceptual measures between HSTs, as outlined in Table 7-2 and Table 7-3.

7.5.3 *Performance measurements*

The HA intervention did not lead to any statistically significant changes in 6s-MPO, MPO FATIGUE%, and PPO FATIGUE% over time; however, statistically significant changes in 6s-PPO [$F_{(2, 22)} = 10.641$, p < 0.001] were evident. PPO significantly increased at Mid-HA (by 76 ± 36 W; d = 0.45) and Post-HA (by 75 ± 34 W;

d = 0.50) compared to Pre-HA by (both p < 0.01). There was no difference in PPO between Mid and Post-HA. The significant increase in PPO persisted at Decay compared to Pre-HA by 65 ± 45 W ($p < 0.05$; $d = 0.41$, see Figure 7-3). There was no statistically significant change in PPO at Decay compared to Post-HA.

7.5.4 Heat acclimation sessions

Group mean (±SD) exposure time, thermal sensation and thermal comfort during each self-directed passive heat acclimation session are presented in Table 7-4.

Table 7-4: Mean ± SD self-reported exposure time, temperature, thermal sensation, and thermal comfort during self-directed passive hot-water immersion (HWI) heat acclimation sessions across the HA protocol.

Session #	Exposure time (min)	Exposure Temp (°C)	Thermal Sensation (AU)	Thermal Comfort (AU)
1	44 ± 6	39.7 ± 0.6	10.4 ± 1.4	5.8 ± 2.8
2	42 ± 3	39.9 ± 1.2	10.8 ± 0.9	7.1 ± 2.4
3	41 ± 4	39.8 ± 1.0	10.5 ± 1.2	6.6 ± 2.3
4	41 ± 4	40.6 ± 1.0	10.4 ± 1.1	7.6 ± 2.1
Group mean	42 ± 7	40.0 ± 1.0	10.5 ± 1.2	6.8 ± 2.5

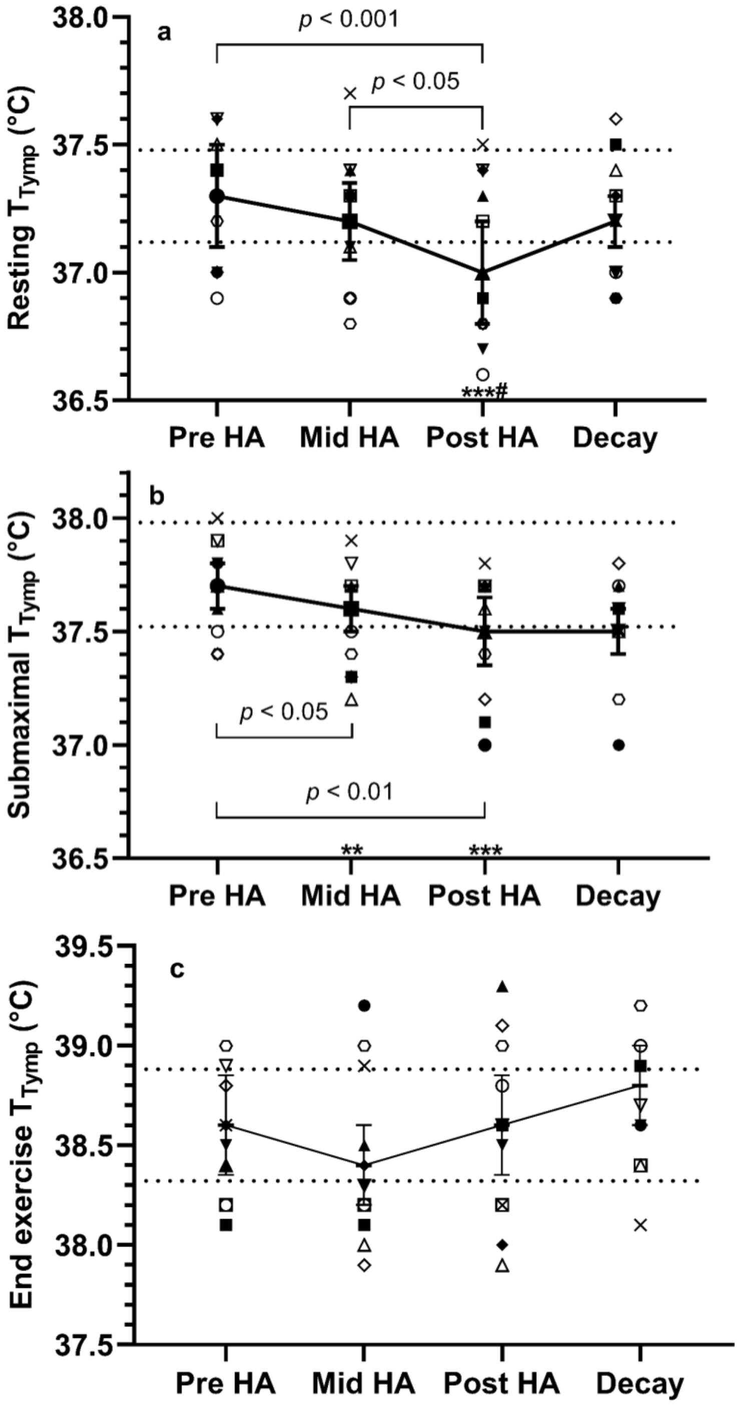

Figure 7-2: Resting (Figure 2a), Submaximal exercise (Figure 2b) and End exercise (Figure 2c) tympanic temperature (°C) during Heat Stress Tests Pre-HA, Mid-HA (three-days), Post-HA (nine days) and Decay (+15 days after Post-HA). The area between the dotted lines represents the smallest worthwhile change. Individual data for each group is represented by; open symbols = represent Natural + IUD; closed symbols represent OCP; linked symbols represent mean ± 95% confidence limits. Where statistical significance occurred, it is indicated. Symbols above the x-axis represent standardised effect sizes (Cohen's *d*) for the following comparisons: * = compared to Pre-HA; # = compared to Mid-HA. The number of symbols represent the size of the effect; 1 = small, 2 = moderate, and 3 = large. HA = Heat Acclimation.

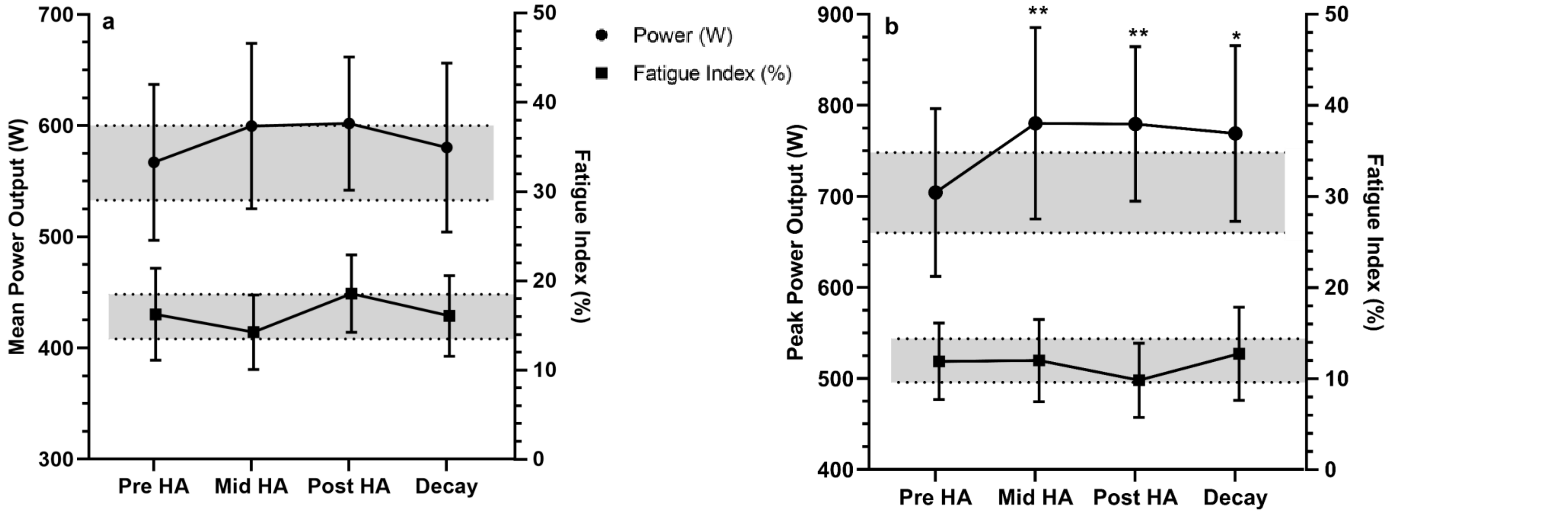

Figure 7-3: Mean (± 95% confidence limits) Power Output (W; closed circles) and Fatigue Index (%; closed squares) during Heat Stress Tests Pre-HA, Mid-HA (5 days), Post-HA (10 days) and Decay (+15 days). Figure 3a represents average 6 s power; Figure 3b represents peak 6 s power. Shaded area represents the smallest worthwhile change for each variable, calculated as 1/3rd of the pre-test CV%. Symbols represent clear differences in standardised effect sizes (Cohen's *d*) for the following comparisons: * = compared to Pre-HA; # = compared to Mid-HA; ^ = compared to Post-HA. The number of symbols represent the size of the effect; 1 = small, 2 = moderate, and 3 = large; HA = Heat Acclimation.

7.6 Discussion

The current study examined physiological, perceptual and performance changes during and following 10-days of (primarily) passive HA integrated into an elite female team sport training program. Our data demonstrated that meaningful changes in resting and submaximal T_{Tymp} were achieved only after the full 10-day HA protocol, however these were not well-retained after 15 days without any further heat stimulus. No sudomotor or cardiovascular changes were apparent during or post HA. Concurrently, meaningful performance increases (specifically R-SPRINT PPO) were evident at both mid- and post-HA and were well-retained after 15 days without any further heat stimulus.

The beneficial changes in resting and submaximal T_{Tymp} seen in the current study are in line with previous findings, whereby decreases in T_c after ≥ 9 days of HA in recreationally-trained females have been demonstrated (Kirby et al., 2019; Mee et al., 2015). Also, in agreement with the current study, both previous studies found no difference in sweat rate. While the similarities between these findings may strengthen the theory of a longer temporal pattern of HA induction in females (Mee et al., 2015), other research with well-trained females has suggested that thermoregulatory adaptation is possible with only 5-days of controlled-hyperthermia HA (Garrett et al., 2019; Pethick et al., 2018). It is likely that the differences between these studies are associated with the initial training status of the athletes, and the cumulative thermal impulse of the HA protocols (Gibson et al., 2019a; Taylor, 2014). Female specific HA protocols that have shown adaptation in 5-days have exceeded the teams' normal peak training load (Pethick et al., 2018), included five consecutive days of 90-min controlled-hyperthermia exercise-based heat exposures (Garrett et al., 2019), or included 20-min sauna exposures before each 90-min controlled-hyperthermia exercise-based heat exposure (Mee et al., 2018). Neither of these approaches are practical to incorporate into an elite team sports training program; hence, the current study provides the first evidence of an ecologically valid HA protocol that can elicit beneficial thermoregulatory and performance changes in such circumstances.

An important consideration for practitioners when scheduling HA into a wider training macrocycle is the time-course of adaptation retention once a heat stimulus is removed (Pryor et al., 2019a). However, none of the previous research into female specific HA protocols have investigated this phenomenon (Garrett et al., 2019; Kirby et al., 2019; Mee et al., 2015; Mee et al., 2018; Pethick et al., 2018), making the current research novel and noteworthy. The current research indicted many positive thermoregulatory effects post-HA, yet these were mostly transient, with only R-SPRINT PPO showing any evidence of retention after 15 days without any further heat stimulus. Hence, given the relatively low intensity and training program integration of the current HA protocol, it provides a framework that could be completed close to departure for a holding camp or competition in a hot environment where additional heat impulses could be prescribed. Alternatively, the prescription of small weekly (1-3 days) 'top-up' heat impulses during the decay period would likely result in greater adaptation retention (Casadio et al., 2016; Weller et al., 2007).

The general view among the literature is that eumenorrheic females encounter a performance disadvantage when exercising in the heat during the luteal phase (Baker et al., 2020). Mechanistically, this view is based on threshold shifts to the vasomotor and sudomotor thermoeffectors (Gagnon & Kenny, 2011, 2012). However, compared to less-trained females, trained females exhibit altered thermoeffector responses and reduced ovarian hormone concentration and fluctuation between menstrual cycle phases, resulting in a greater capacity to deal with a heat load (Kuwahara et al., 2005). Importantly, most previous research concerning the impact of acute heat, or heat adaptation have been based on performance during fixed-intensity exercise, thus not allowing for behavioural thermoregulation (Schlader et al., 2011c; Vargas et al., 2019). However, even though the current study was underpowered to detect group differences, their appeared to be no significant differences between the Natural + IUD and OCP groups in physiological, perceptual, or performance metrics typically influenced by menstrual phase in less well-trained females (Baker et al., 2020). Thus, rather than intrinsic physiological changes, behavioural changes allowing for greater effort, and correspondingly greater peak power output during self-paced repeated sprint exercise may explain the increase in RPE demonstrated in the current study.

7.6.1 Perspectives and considerations

The current study indicated passive HA was beneficial for repeated sprint performance both over short- and medium-term HA periods. In rugby sevens (and most team sport) situations, work rate is often determined by the individuals and playing style of the opposition (Marrier et al., 2018; Ross et al., 2015b). In this regard, an improvement in sprint performance is practically important as the ability to maintain repeated sprint performance can determine outcomes within a game. Although short-term, and/or low thermal impulse acclimation protocols do not induce complete HA adaptations, these protocols may be practically useful when other training priorities take precedence.

The population in the current study allows for unique and ecologically valid findings; however, the nature of undertaking research in such an elite environment involves several limitations. Namely, it precludes the use of a control group which means that we cannot disqualify that the current findings are not due to general training adaptations. Nonetheless, it is unlikely that any meaningful non-HA-specific training adaptation occurred during this time, due to the calibre and training status of athletes involved in the study (Lorenzo et al., 2010). Furthermore, the study design is limited by the concurrent training periodisation, whereby controlling for menstrual cycle status is not realistic within the constraints of a professional sporting context. While menstrual cycle status was recorded using a self-reported questionnaire, protected heath information limited us from reporting whether these participants were on active or placebo phases of the OCP.

The current study reported oral contraceptive use and menstrual cycle status without any subsequent methodological control. As such, the current study was underpowered to determine any differences between the Natural + IUD and OCP groups; appropriate consideration of the menstrual cycle in future research may reduce variability in experiments and aid researchers in detecting differences between treatments or groups, including in measurements of body temperature (Baker et al., 2020).

7.7 Conclusion

The current investigation demonstrates a novel 10-day HA (primarily) passive protocol that elicits minor thermoregulatory and performance benefit when integrated into an elite team's training program. Furthermore, this data showed for the first time that such a protocol does not provide a sufficient thermal impulse for adaptations to be retained after 15-days with no further heat stimulus. Future work should endeavour to determine an ecologically valid HA protocol that is likely to promote more complete adaptations in highly trained female athletes.

Chapter Eight Small performance effects of a practical cooling strategy in elite team sport athletes

Fenemor, S. P., Gill, N. D., Driller, M. W., Mills, B., Sella, F., & Beaven, C. M. (2022). Small performance effects of a practical cooling strategy in elite team sport athletes. *Research Quarterly for Exercise and Sport*. In review

Prelude

Chapter Six and Chapter Seven demonstrated the utility of two different heat acclimation protocols within both male and female elite rugby sevens teams. With cooling being an important component of heat management, Chapter Eight investigates how the use of commonly performed cooling strategies impact upon the physiological, perceptual, and performance outcomes during a sport-specific heat response test, providing important information to practitioners regarding cooling strategy use during subsequent competition in hot and humid conditions.

8.1 Abstract

Purpose: The ingestion of ice slurry and application of ice towels can elicit favourable physiological, perceptual, and performance benefits when used individually; however, the combined use and effectiveness of these practical cooling strategies have not been assessed using a sport-specific performance test, based on actual match demands, in an elite team sport context.

Methods: Ten non-heat acclimated elite male rugby sevens athletes undertook two cycling heat response tests (HRT) designed to be specific to the demands of rugby sevens in hot conditions (35 °C, 80% RH). In a crossover design, the HRTs were conducted with (COOLING) and without (HOT) the combined use of internal (ice slushy ingestion) and external (application of ice towels to the head, neck, and face) pre- and per-cooling strategies. Physiological, perceptual and performance variables were monitored throughout each HRT.

Results: COOLING resulted in reductions in mean tympanic temperature (-0.4 ± 0.2 °C; d =1.18); mean heart rate (-5 ± 8 bpm; d =0.53); thermal discomfort (-0.5 ± 0.9 AU; d =0.48); and thirst sensation (-1.0 ± 1.1 AU; d =0.61) during the HRT. COOLING also resulted in a *small* increase in 4-min time trial power output (by 7 ± 33 W, ~3%; d =0.35) compared to HOT.

Discussion: A combination of internal and external pre- and per-cooling strategies can result in a range of small physiological, perceptual, and performance benefits during a rugby sevens specific HRT, compared to undertaking no cooling. Practitioners should include such strategies when performing in hot conditions.

8.2 Introduction

Rugby sevens is characterised by repeated bouts of high-intensity running, frequent contacts, sprints, skill, and spatial awareness, played over 2x 7-min halves, with seven players per team (Ross et al., 2015a). International rugby sevens teams compete in the World Rugby Sevens Series, along with pinnacle events such as the Olympic and Commonwealth Games. Many of these events are scheduled in hot summer environments, for example, temperatures of 45 °C (113 °F) were recorded during a recent Sydney tournament (unpublished field observations), and the (delayed) Tokyo 2020 Summer Olympics were predicted to, and realised to be, the hottest Olympics on record (Gerrett et al., 2019b; Kakamu et al., 2017). These challenging environmental conditions, along with the repeated high-intensity nature of rugby sevens combine to present a thermoregulatory challenge that is likely to impact performance (Fenemor et al., 2021). In this regard, the importance of appropriate heat management strategies are well indicated (Racinais et al., 2015).

While heat acclimation is commonly considered the most important heat management strategy (Gibson et al., 2019a), the application of pre- and/or per-cooling can alleviate environmental heat stress on the day of performance (Bongers et al., 2017; Douzi et al., 2019; Ruddock et al., 2017). Pre-cooling aims to lower core and skin temperature (T_c; T_{skin}) prior to the onset of exercise, thereby attenuating the adverse effects of heat stress, and increasing the capacity for metabolic heat production and heat gain. Thus, pre-cooling enables athletes to perform more work before an individual 'critical T_c' is reached (i.e., >40 °C) (Bongers et al., 2017; Tyler et al., 2015). Per-cooling aims to mitigate the exercise-induced rise in T_c, thus delaying the onset of hyperthermia-induced fatigue, whilst also providing perceptual benefit (Bongers et al., 2017; Cao et al., 2022; Vargas et al., 2019). In terms of pre-cooling, the performance benefits of cold-water immersion (CWI) are well-established for both intermittent-sprint and prolonged endurance exercise (Bongers et al., 2017; Duffield et al., 2010). Despite these well-established benefits, CWI pre-cooling still requires significant logistical challenges to be overcome for application in a field setting (Gibson et al., 2019a), and the practicalities within athletic training and performance require substantial thought, especially considering the positive effects of elevated muscle temperature on performance (Bergh & Ekblom, 1979; Racinais & Oksa, 2010). Accordingly, a mixed-methods approach, combining both internal cooling with practical localised external cooling (i.e., application of ice towels) may be more feasible, and preferable for athletes and practitioners (Aldous et al., 2018; James et al., 2015; Minett et al., 2011).

Typically, internal cooling strategies involve the consumption of ice slurry, with the bolus of ice being melted in the stomach and small intestine, causing a small decrease in T_c (Siegel et al., 2010). In order to avoid the negative effects of ingesting a large bolus of ice slurry (such as headache and gastrointestinal discomfort), recommendations suggest that ice slurry should be ingested at a rate of 1.25 $g \cdot kg^{-1}$ every 5 min for 30 min before a performance [equating to 600 g of slurry for an 80 kg athlete; (Racinais et al., 2015)] External cooling strategies act to lower T_{skin}, which may be associated with reduced thermal discomfort and facilitate behavioural thermoregulation (Cao et al., 2022; Schlader et al., 2011b). An immediate reduction in thermal discomfort can result when a cold stimulus is applied to the head, face, and neck regions of a heat-stressed individual, due to these regions exhibiting greater alliesthesial sensitivity than the rest of the body (Cotter & Taylor, 2005). As such, cooling the head and neck regions has been demonstrated as an effective method to mitigate perceptual strain and improve performance in the heat in endurance (Schlader et al., 2011a; Tyler & Sunderland, 2011; Tyler et al., 2010), and repeated sprint contexts (Sunderland et al., 2015). Notably, Sawka and colleagues (2012) suggested that cooling the core (i.e. internal cooling) without a concurrent reduction in T_{skin} (i.e. external cooling) will decrease the core to skin thermal gradient, thus impairing the ability of a human body to dissipate heat to the environment; hence, combining internal and external cooling may act to provide an increased heat storage capacity, alongside a reduced rate of heat storage during exercise (James et al., 2015).

Each sport or athletic competition involves its own circumstances that determine per-cooling method practicality (Russell et al., 2015), for example, in rugby sevens only short breaks (i.e. ~ 2 min at halftime) provide the only planned opportunity for cooling strategies to be implemented. During such breaks, short, non-obtrusive interventions are the most practical, such as the application of ice towels, or ingestion of small amounts of ice slurry. Given the increased thermoregulatory challenge of undertaking repeated high-intensity exercise in hot environmental conditions (Ekblom et al., 1971; Fenemor et al., 2021), specific evidence is needed to guide practitioners on the use of previously described cooling strategies (Bongers et al., 2017). Therefore, the aims of the current research were to evaluate the effectiveness of a combined internal and external cooling protocol using the ingestion of ice slurry, and the application of ice towels to the head and neck, before and during a repeated high-intensity heat response test, designed to simulate a game of rugby sevens. We hypothesised that combined internal and external pre- and per-cooling would result in enhanced physiological, perceptual, and performance responses during a rugby sevens specific heat response test.

8.3 Methods

8.3.1 Subjects

Data was collected from ten non-heat acclimated elite male rugby sevens athletes (mean ± SD, age: 25 ± 3 years; body mass 95.3 ± 6.5 kg; height 1.90 ± 0.03 m) of a single international team (current world champions and Olympic silver medallists). Written informed consent was collected from all participants prior to the beginning of the study, and the procedures of the study were approved by the Human Research Ethics Committee at the University of Waikato (HREC2018#64). Athletes were asked to consume the same food and abstain from alcohol and caffeine in the 12 hours before each testing session. All trials took place in local springtime conditions (mean daytime high ~18 °C) throughout the teams' pre-season to avoid any natural heat acclimatisation. Participants were asked to refrain from strenuous exercise outside of the laboratory 48 h before each testing session.

8.3.2 Design

In a crossover design, participants undertook two heat response tests (HRT) across consecutive weeks (HOT; COOLING) in an environmental chamber maintained at 35 °C, 80% RH. Participants performed all testing sessions at the same time of day (Monday mornings) across two weeks to account for circadian rhythms (Reilly & Brooks, 1986). All participants were familiar with the testing protocol, as this has been evaluated recently from the same laboratory (unpublished findings). During both HRTs all participants consumed 640 mL of 6% carbohydrate sports drink (Gatorade, The Gatorade Company, Inc. Chicago, Illinois, United States) prepared as an either ice slurry during COOLING (1 °C; 200 ml pre-warm-up, 200 mL post warm-up, 120 mL at half-time, 120 mL pre time-trial), or at room temperature (22 °C) during HOT. Additionally, during COOLING, participants applied towels that had been immersed in ice water to the head and neck for 60 s.

Condition		Warm Up		1st Half	H/T	2nd Half		Time-Trial
HOT	##		##		#		#	4-min
COOLING	**		**^		*^		*^	4-min

	5-min DS, 4-min cycle at 1.5 $W\cdot kg^{-1}$, 2-min DS, 2-min cycle at 2.0 $W\cdot kg^{-1}$, 2-min DS, 30 s cycle at 3.0 $W\cdot kg^{-1}$, 1-min rest, 30 s cycle at 3.0 $W\cdot kg^{-1}$, 2-min rest
	30 s cycling @ 3 $W\cdot kg^{-1}$: 40 s rest repeated six times. Six down-ups after every 2nd interval.

= 120 ml sports drink; ## = 200 ml sports drink; * = 120 ml ice slurry; ** = 200 ml ice slurry; ^ = ice towel (60s)
H/T = 2-min half time; DS = dynamic stretching

Figure 8-1: Schematic of the HOT and COOLING conditions

8.3.3 Heat response test

Participants entered the environmental chamber and completed a 19-min progressive-intensity, standardised warm-up (see Figure 8-1) followed by a repeated interval protocol and a 4-min time trial (TT). The repeated interval protocol consisted of 30 s cycling at 3.0 $W\cdot kg^{-1}$, followed by 40 s rest, repeated 12 times with a 2-min half-time break after interval 6. Immediately following every 2^{nd} interval, participants also performed six down-ups (to simulate rucking type movements in rugby sevens). The design and content of the repeated interval protocol was chosen as it replicates game average high-intensity running volume, work: rest ratios (30 s: 40 s), and dynamic rucking type movements in rugby sevens (~15 per match) (Ross et al., 2015a). This cycling-based protocol was evaluated against a similar running-based protocol in our lab, indicating that it can replicate the perceptual but not physiological stress associated with repeated high-intensity running in the heat. During the 4-min TT the display monitor of the cycle ergometer was covered, and verbal cues given by a researcher at 1000, 2000, 2500, and 2800 m. A 4-min TT was chosen as participants were familiar with this cycle test as it is commonly used as an off-feet conditioning session during their normal training, and it has been shown to have high level of test-retest reliability (CV < 3%) (Driller et al., 2014). All cycling was performed on a calibrated cycle ergometer (WattBike Ltd, Nottingham, UK).

8.3.4 Physiological measurements

Tympanic Temperature (T_{Tymp}; Braun ThermoScan® 7 IRT6520, Braun GmbH, Kronberg, Germany) and Heart Rate (HR; Polar H10, Polar Electro Oy, Kempele, Finland) were sampled at 0 min, post warm-up, after intervals 3 and 6; at the end of half time; after intervals 9 and 12; Pre TT and End TT. The mean of values collected after intervals 3 and 6 was taken to calculate the first half measurement, likewise for the second half with intervals 9 and 12 (as shown in Figure 8-2). Each T_{Tymp} measurement was sampled in duplicate, the mean of which was recorded for analysis. T_{Tymp} was chosen as our method of assessing body temperature as it has been previously demonstrated acceptable agreement with assessment of core temperature via telemetry pill when exercising in the heat (Fenemor et al., 2020).

Before the start of each test the skin of the right shoulder blade was cleaned with distilled water and dried, before adhesive gauze sweat patches (Tegaderm+Pad, 3M, Loughborough, UK) were applied. At the completion of each test, sweat patches were immediately placed into sealed containers and frozen until analysis. Sweat sodium concentration was determined using absorbance photometry (Cobas C111 analyser, Roche, AG Basel Switzerland). To estimate sweat rate, towel-dried, nude body mass was recorded to 0.1 kg using digital scales (Seca 877, Seca, Hamburg, Germany) before and immediately after each session, this value was adjusted for ingested liquid during the test (640 mL) and then converted to a rate ($kg \cdot hr^{-1}$).

8.3.5 Perceptual measurements

Rating of perceived exertion [RPE; 6-20 scale; (Borg, 1970)], thermal sensation [TS; 1-13 point scale;], thermal discomfort [TDC; 1-10-point scale; (Gagge et al., 1967)] and thirst sensation [Thirst; 1-9 point scale; (Riebe et al., 1997)] were collected at the same time points described above for physiological measurements during the HRT's.

8.4 Statistical analysis

Raw data in tables and text are presented as mean ± SD with the mean differences (MD) and uncertainty of estimates shown as MD ± 95% confidence limits (CL). The mean of all data points was calculated and used in the corresponding analysis, presented in Table 8-1. For all variables, two-way repeated measures ANOVA was used to determine if there were differences between conditions across time. The Šídák – Bonferroni correction was used to correct for pairwise multiple comparisons. Normality and homogeneity of variance of residuals were checked using quantile-quantile (Q-Q) and scatter plots, which were deemed plausible in each instance. Where there was a main effect, magnitudes between each measurement period were determined and expressed as both mean differences ± 95% confidence limits (CL) and standardised effect sizes (Cohen's *d*). If the 95% CL for Cohen's *d* overlapped positive and negative trivial (± 0.20) values, the effect was deemed *unclear*. Substantial clear effects were described using standard thresholds of < 0.20 *trivial*, 0.20 – 0.49 *small*, 0.50 – 0.79 *moderate*, and > 0.80 *large* (Cohen, 1988).

8.5 Results

The interaction effect between time and condition was not statistically significant for any variable. Therefore, an analysis of the main effects for time was performed for all variables; these indicated that the main effect was statistically significant for T_{Tymp} [$F(6, 54) = 209.5$, $p < .0001$]; HR [$F(3, 28) = 305.8$, $p < .0001$]; TS [$F(6, 54) = 37.3$, $p < .0001$]; TDC [$F(2, 16) = 53.3$, $p < .0001$]; and Thirst [$F(3, 23) = 16.1$, $p < .0001$]. There were no statistically significant main effects for any other variables. Pairwise comparisons were then run to determine any differences at each measurement timepoint between HOT and COOLING conditions. These indicated that COOLING resulted in significant reductions in T_{Tymp} during the First half, at End half-time, during the Second half, Pre-TT, and End-TT (all $p < 0.05$, Figure 8-2). These significant reductions in T_{Tymp} caused in a *large* significant reduction in overall mean T_{Tymp} across the entire HRT (Table 8-1). COOLING resulted in a *moderate* decrease in mean HR and Thirst sensation, a *small* decrease in mean TDC, and a *small* increase in TT power; however, these did not reach statistical significance ($p > 0.05$). Group mean differences (± 95% CL), effect sizes, and statistical significance for all variables are presented in Table 8-1.

Table 8-1: Grouped mean (± SD) and mean differences [MD ± 95% CL (Cohens d)] for all variables for HOT and COOLING Heat Response Tests.

	HOT	COOLING	HOT - COOLING
T_{Tymp} (°C)	37.9 ± 0.3	37.5 ± 0.3	-0.4 ± 0.3 (1.18) *large**
Heart Rate (bpm)	155 ± 8	150 ± 10	-5 ± 8 (0.53) *moderate*
TS (AU)	10.8 ± 0.7	10.6 ± 0.4	-0.1 ± 0.6 (0.16)
TDC (AU)	6.6 ± 1.1	6.1 ± 0.9	-0.5 ± 0.9 (0.48) *small*
RPE (AU)	16.2 ± 0.8	16.2 ± 0.8	0.0 ± 0.7 (0.08)
Thirst (AU)	3.8 ± 1.4	2.9 ± 1.1	-1.0 ± 1.1 (0.61) *moderate*
Sweat rate ($kg \cdot hr^{-1}$)	1.5 ± 0.3	1.5 ± 0.4	0.0 ± 0.3 (0.06)
Sweat [Na^{+}] (mmol/L)	69.7 ± 20.1	69.4 ± 18.9	-0.3 ± 15.3 (0.01)
4-min Time Trial (W)	290 ± 34	297 ± 36	-7 ± 33 (0.35) *small*

Comparisons are represented as mean difference ±95% CL, brackets represent Cohen's *d* which are qualitatively described in italics. Significance is indicated as * $p < 0.05$; AU = arbitrary units; TS = Thermal sensation; TDC = Thermal discomfort; RPE = Rate of perceived exertion.

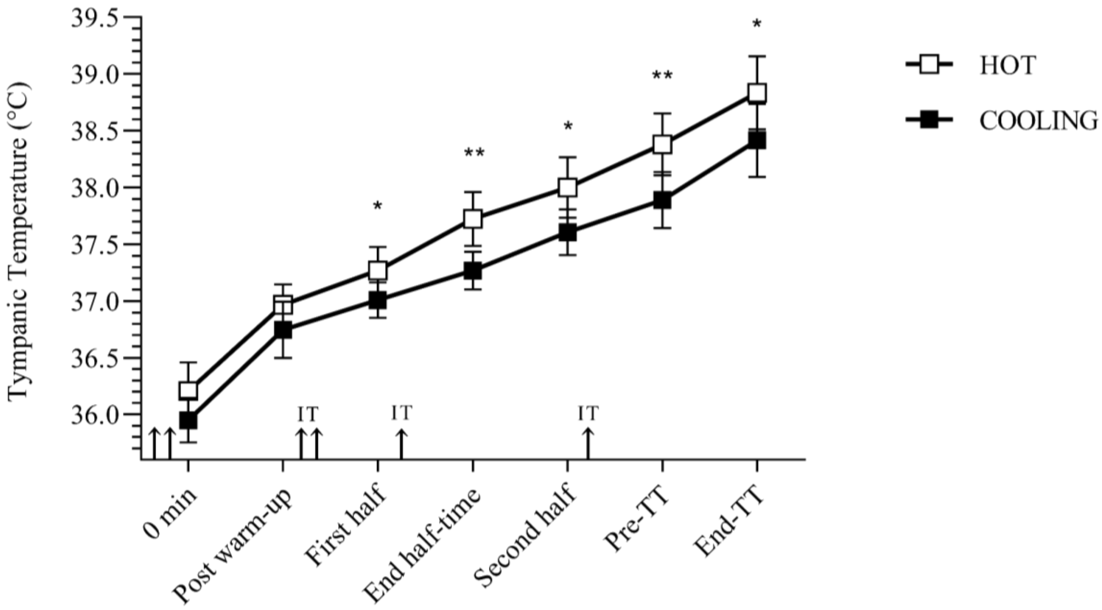

Figure 8-2: Mean (± SD) tympanic temperature (°C) at each measured timepoint for the two interventions. ↑↑ indicates where 200 mL ice slurry/room temperature fluid was ingested; ↑ indicates where 120 mL ice slurry/room temperature fluid was ingested; IT indicates where ice towels were applied to the head, neck, and face for 60 s. * = $p \leq 0.05$; ** = $p \leq 0.01$.

8.6 Discussion

The current study examined the combined use of internal and external cooling strategies delivered via the use of ice slurry ingestion and the application of ice towels to the head, neck, and face before and during a repeated high-intensity exercise heat response test. The findings indicated that COOLING resulted *moderate to large* beneficial physiological changes (T_{Tymp} and HR) and *small to moderate* beneficial changes in indices of thermal perception (TDC and Thirst). Furthermore, there was a *small* increase in mean TT power output (3%) during COOLING compared to HOT.

The beneficial physiological changes presented in the current study (Figure 8-2 and Table 8-1) support the contention that combined internal and external cooling are effective at blunting the thermal strain caused by repeated high-intensity exercise in the heat. In terms of T_{Tymp}, it was notable that the constant application of cooling stimuli had the most benefit towards the end of the HRT (Figure 8-2). A similar T_c profile was demonstrated by Naito and colleagues (2018) during simulated tennis match-play in the heat. The authors indicated that the consumption of 1.25 $g{\cdot}kg^{-1}$ ice slurry at every rest break was significantly more effective at attenuating the increase in T_c than the same volume of cold-water; however, the blunted increase in T_c was only evident during the second half of exercise. In the current study, COOLING resulted in a 0.4 °C mean reduction in T_{Tymp} across the entire HRT. Such reductions in body temperature arising from ice slurry consumption are thought to benefit performance due to enhanced absolute heat storage capacity that prevents or delays central fatigue, which results in greater exercise intensity being permitted (James et al., 2015). Furthermore, it has been indicated that ice slurry acts upon thermoreceptors within the splanchnic region (Guest et al., 2007), and the frontal cortex of the brain (Onitsuka et al., 2018). Both thermoreceptors may activate pleasure centres of the brain, possibly leading to athletes developing a false sense of the overall thermal strain they are experiencing (Guest et al., 2007; James et al., 2015).

A previous team sport investigation indicated that 30-min of mixed-method pre-cooling (combination of ice slurry and ice packs) can augment physical performance within the first half of a simulated soccer performance test in the heat (Aldous et al., 2018). Interestingly however, the authors revealed that the subsequent application of half-time cooling strategies (15-min break) had no effect on physiological, perceptual, or performance measures throughout the second half. The authors speculated that cooling-related perturbations in muscle temperature, acting to decrease muscle contractility, may have potentially decreased repeated-sprint ability during the second half. In the current study, physiological, perceptual, and performance benefit were evident after the half-time break, possibly related to the comparatively short half-time break (2 min), which would not allow significant reductions in muscle temperature. Similarly, Minett and colleagues (2011) had previously indicated that mixed-method external cooling (ice packs, towels, and vest) between halves (5 min) significantly improved total distance covered (by 5%) during the second half of a self-paced intermittent sprint exercise protocol in hot conditions. Taken together, it seems that aggressive short-duration mixed-method half-time cooling strategies, that fit within the practical limits of the break interval, may be the most effective for physiological, perceptual, and performance benefit (Russell et al., 2015).

The results of the current study further support those of a recent meta-analysis, which indicated that per-cooling using a combination of internal cooling (i.e. ice slurry ingestion) and external cooling (particularly on the face, neck, and torso) provide the greatest benefit for aerobic performances when exercising in the heat (Douzi et al., 2019). Furthermore in the current study, COOLING resulted in less thermal discomfort compared to HOT, supporting the concept that alleviating perceived thermal stress during an exercise performance in the heat can increase work output during self-paced exercise (Cheung, 2010). In the current study, the same volume of fluid was ingested in both conditions; however, Thirst sensation was decreased in the COOLING condition, possibly due to the stimulation of sensory nerves on the tongue and oropharyngeal region (Saldaris et al., 2020). Although satiation of thirst can be beneficial for cognitive function and reaction time tasks (Edmonds et al., 2013), the current findings indicate that caution must be taken when athletes use ice slurry before and during exercise performances in the heat, due to the potential development of dehydration.

8.7 Practical applications and considerations

It was shown that the combined use of internal and external pre and per-cooling strategies were effective at blunting the physiological and perceptual heat stress associated with exercising in the heat, along with contributing to practically important increases in self-paced high intensity exercise performance. Although this investigation was conducted within elite rugby sevens athletes, the findings are transferrable to other Olympic / elite team and invasion sport contexts. While the results are indicative of the importance for practitioners to include practical cooling strategies within a game-day program, the small enhancements observed indicate that the larger performance benefits of heat acclimation as a pre-competition heat management strategy must not be ignored. In this way, future research should investigate the application of similar practical cooling strategies within an elite heat acclimated population. Per-cooling during team sports are likely to be opportunity-based (i.e., breaks in play); as such, the application of ad-libitum cooling strategies may induce different results than those demonstrated in the current study. Furthermore, despite the current internal and external cooling strategies being similar to those suggested as most beneficial in the meta-analysis of Douzi and colleagues

(2019), it is unknown whether other similar cooling methodologies would have resulted in the same demonstrated effects. While the ecological validity and high calibre of athletes are strengths of the current study, it is acknowledged that research in such an elite sport setting precluded the use of a control group or a larger sample size.

8.8 Conclusion

The current study demonstrated that the combination of internal and external pre- and per-cooling strategies can result in physiological, perceptual and performance benefits, compared to undertaking no cooling when exercising in hot and humid conditions (35 °C, 80% RH). It is recommended that practitioners include a combination of practical internal and external cooling strategies within their heat management plan when performing in hot conditions. Future research should consider the application of such strategies within an elite heat acclimated population, to determine the benefits of cooling over and above heat acclimation.

Chapter Nine General discussion

9.1 Thesis aims

This thesis sought to develop and implement heat management strategies for international elite men's and women's rugby sevens teams competing in hot and humid conditions. Underlying this purpose was to ensure that our New Zealand national rugby sevens teams were adequately prepared for the un-paralleled environmental conditions at the Tokyo 2020 Olympic Games. The first three of six experimental chapters incorporated research designed to characterise the physiological, perceptual, and performance perturbations that undertaking rugby sevens specific exercise in hot and humid conditions involves. The following three experimental chapters built upon these characterisations by investigating practical, training-integrated interventions, designed to alleviate the stressors that collectively impair performance. With very limited previous research on heat management strategies in rugby sevens, particularly in an elite setting, the research within this thesis is among the first to address these critical areas of preparation and performance in an elite rugby sevens context.

Study One (Chapter Three) was conducted to assess the validity of two practical measures of T_c and T_{sk} during exercise in hot and humid conditions, that could be used during subsequent investigations within the thesis. Study Two (Chapter Four) involved the characterisation of T_c, and physiological and performance characteristics that mediate T_c change across a rugby sevens tournament played in hot and humid conditions. Following this, Study Three (Chapter Five) investigated the application of an off-feet (cycling) heat response test that would be practical to use within the training weeks of an elite rugby sevens team. This test was an important 'tool' for the assessment of later heat acclimation and cooling studies in the thesis. Given that best-practise heat management strategies include heat acclimation in the lead up to competitions in hot and/or humid conditions, Study Four and Study Five were concerned with the assessment of practical heat acclimation strategies, integrated within the normal training weeks of international elite men's (Chapter Six) and women's (Chapter Seven) rugby sevens team. Finally, Study Six (Chapter Eight) investigated the application of practical cooling strategies within an international elite men's rugby sevens team.

This general discussion will summarise the findings of each of the experimental chapters within the thesis. Following this general discussion, practical recommendations, and limitations of the work within this thesis are provided, along with suggesting fields where future elite heat management research could extend.

9.2 Summary of findings

9.2.1 Characterisation studies

Study One (Chapter Three) aimed to assess whether minimally invasive, practical devices designed to measure T_c and T_{skin} pre-, during-, and post-exercise in the heat are valid and reliable alternatives for laboratory-based, invasive, and expensive measures of T_c and T_{skin}. The results of study one demonstrated the Braun ThermoScan® 7 device to be a valid tool when measuring T_{Tymp} during exercise in the heat. Given the uncertainty of other tympanic temperature devices, the confirmation of validity of the Braun ThermoScan® 7 was an important finding, given that this device was subsequently utilised throughout Chapter Three, Seven and Eight. While the Braun ThermoScan® 7 proved valid for T_c estimation during exercise in the heat, caution should be taken when using such devices for temperature monitoring during a recovery period due to the tendency for tympanic devices to underestimate T_c during recovery.

As observed by Morán-Navarro et al. (2018), other devices may be less valid and less reliable than the Braun ThermoScan® 7, as such, it must be noted that the results of

Study One are specific to the devices that were assessed during that study. Historically, the assessment of T_{Tymp} as a substitute for T_c has been questioned within exercise physiology and performance science contexts (Casa et al., 2007; Taylor et al., 2014). For a practitioner however, the current findings indicate that a tympanic thermometer may be acceptable when exercise induced increases in T_c need to be monitored. However, with the current findings, and that of previous research (Ganio et al., 2009b; Huggins et al., 2012; Morán-Navarro et al., 2018) demonstrating T_{Tymp} to underestimate T_c during a recovery period, it is not recommended that such devices are used for medical and/or heat illness monitoring purposes. Previously it has been suggested that there is a direct relationship between tympanic and brain temperatures (Mariak et al., 1994), possibly related to preferential brain cooling, resulting from forced vascular convection and conductive cooling (Cabanac & Caputa, 1979; Cabanac et al., 1987). Given that the brain integrates thermoregulatory inputs from a range of receptors to elicit a thermoregulatory response, measuring temperature proximal to the brain may have further practical relevance, as opposed to that of deep body temperature, if indeed such measurements are performed using valid and reliable tools.

Study Two (Chapter Four) aimed to characterise T_c profiles during an international rugby sevens tournament performed in hot and humid conditions; furthermore, the study aimed to characterise physiological and performance metrics that mediate T_c change across such a tournament. At the time of this data collection, such applied characterisation of T_c was particularly novel; however, soon after the completion of data collection Taylor et al. (2019b) published a similar T_c characterisation, using the Scotland rugby sevens team across WRSS tournaments in Dubai and London. The findings of Taylor et al. (2019b) indicated that peak T_c values approached thresholds associated with EHI (>40 °C) and exceeded those demonstrated to reduce repeated sprint performance (>39 °C), regardless of the environmental conditions in which the WRSS tournament was played.

Of note, there were some key differences between the study of Taylor et al. (2019b) and Study Two in the current thesis. Namely, the environmental conditions in the current study (~30 °C, 75% RH) were objectively more similar to those predicted at the Tokyo 2020 Olympic Games, which provided practitioners with important information regarding individual responses during rugby sevens competition in such an environment. In these hot and humid conditions, we demonstrated that T_c during warm-ups and games regularly exceeded 39 °C. Most importantly, it was demonstrated that commonly measured external load variables such as playing minutes, high-speed distance, and total distance can significantly predict post-game T_c during an international rugby sevens tournament played in hot and humid conditions. Furthermore, post warm-up T_c significantly predicted post-game T_c. Neither of these findings had previously been described. During each tournament day, sequential increases in mean T_c post warm-up were shown, and all post-baseline measures were greater than baseline on Day One and Day Two, respectively.

Our findings indicated a cumulative increase in T_c across the tournament, particularly during non-competition exercise. These novel findings have important implications for practitioners, considering that external load metrics are readily (and instantly) available for most elite team sports. As such, the adjustment of non-competition exercise (i.e., primers, warm-ups) when competing in challenging environmental conditions is an easy and practical solution to alleviate subsequent heat stress during competition. This data provides important information for coaches regarding player management during environmentally stressful rugby sevens tournaments. For example, nearly three-quarters of the athletes in the current study demonstrated a T_c approaching, and exceeding those associated with impaired repeated sprint performance [39 °C; (Girard et al., 2015)], and EHI symptoms [>39.5 °C; (Racinais et al., 2015)]. The investigation also identified individuals that were susceptible to repeated instances of high T_c across the tournament, with four individuals reaching a T_c of > 39.0 °C on more than one occasion. From an applied perspective, this identification of thermally susceptible individuals is important for practitioners. Such identification provides practitioners with the ability to individualise cooling strategies, nutrition/hydration strategies, and off-field load management to limit the potential detrimental performance and health effects of the observed cumulative heat load. Taken together, these data should provide practitioners impetus to develop individualised tournament load management and cooling protocols that aim to limit prolonged exposure to high core temperatures, thus optimising player readiness.

During a similar period to the current study, Henderson and colleagues (working with the Australian women's rugby sevens team) produced a characterisation of T_c with elite female athletes across a WRSS tournament day played in temperate conditions (WBGT = 18.5 to 20.1 °C) in Sydney, Australia (Henderson et al., 2020a). While the authors described similar T_c profiles to the male data presented herein, they found no association between changes in T_c and reductions in external load measures. These differences between the findings of male and female T_c characterisations may be due to technical and/or tactical influences of the games which impact their physical demands (Henderson et al., 2018); or individual variation in the relationship between high T_c and repeated sprint performances (Girard et al., 2015). The conclusions from Study Two of the current thesis, along with those by Taylor and colleagues (2019b); and Henderson and colleagues and (2020a) are based on small sample sizes (n ~ 12) across one or two tournaments. As such, there is an opportunity for future research to make similar characterisations across multiple match days and/or tournaments to provide greater statistical power and limit the variance due to technical and/or tactical game influences.

An important component of heat acclimation research is the assessment of physiological, perceptual, and performance changes resulting from a heat acclimation protocol. Traditionally, this has been done using heat response, or heat stress testing (HRT or HST). As such, the aim of Study Three was to assess whether a specifically designed off-feet (cycling) heat response test could provide a similar physiological stimulus as a running test, without the associated mechanical load. Furthermore, the physiological and performance responses of elite rugby sevens players between a ambient environment (20 °C, 50% RH) and the thermally challenging conditions expected at the Tokyo 2020 Olympics (35 °C, 80% RH) were investigated. This investigation was the first, to our knowledge, to investigate and compare the effects of acute heat stress during both on and off-feet exercise in an elite rugby sevens population.

As hypothesised, it was demonstrated that acute heat stress resulted in large increases in physiological and perceptual thermal strain when compared to the same exercise stimulus performed in temperate conditions. Furthermore, it was shown that these increases in thermal strain were associated with a *large* performance decrement during a 1200 m running TT (66 ± 42 s; ~25%). Study Three provided further evidence of intraindividual variability in many physiological and perceptual responses to heat stress, along with large variability in the performance decrement between individuals. In the context of the current thesis, this verification of impaired performance in an environment representative of that expected at the Tokyo 2020 Olympic Games, was important to establish. Furthermore, identifying individuals susceptible to heat stress and/or performance decrements in both real-life (Study Two) and laboratory contexts (Study Three) allowed practitioners to develop individualised heat management strategies to optimise player readiness. It must be noted that while the test employed in Study Four was designed to mimic the physiological strain of rugby sevens, the test lacked specificity in terms of replicating the collisions/impacts involved in a rugby sevens game.

In Study Three, the 1200 m TT was included as a performance variable as it is the same distance as the athletes usual running performance test (Bronco), while the 4-min TT was chosen as it had a similar completion time to the running 1.2 km shuttle run test. Even though these tests provided simple and familiar performance metrics for athletes and practitioners, these types of long-duration high-intensity aerobic efforts are uncommon for rugby sevens athletes (Henderson et al., 2018; Ross et al., 2015a), perhaps limiting the transferability of these findings to other repeated high intensity sports. Of note, when comparing running to cycling HRT's, *moderate* to *large* physiological differences were evident; whereas there were no clear differences on any variables associated with perceptual heat stress. As such, when using cycling as an exercise heat stress, methods to exacerbate the thermal impulse should be considered, such as increasing exercise time/intensity or including 'thermal pre-loading' using passive methods. Moreover, using cycling rather than running is likely to be appealing to practitioners as this mode allows for running load to be reserved for specific on-field training, which may reduce injury risk, compared to including additional running load.

9.2.2 Intervention studies

Chapter Seven (Study Four) investigated the effectiveness and retention of two-weeks of mixed-methods heat acclimation, integrated within an elite male rugby sevens teams training program. Heat acclimation is well-regarded as the best countermeasure to minimise heat-induced physiological strain, lower the incidence of heat-illness, and improve athletic performance in the heat for team sport athletes (Pryor et al., 2019a; Racinais et al., 2015). However, consideration of the multiple factors influencing heat acclimation induction and retention, along with practical considerations for integration within an elite training schedule, creates complex questions regarding the optimal design of heat acclimation protocols within an elite sporting context. While the recent reviews of Pryor et al. (2019a) and Gibson et al. (2019a) provide practitioners with an excellent theoretical background into heat acclimation methodology, along with some examples of possible heat acclimation protocols, these reviews are largely based on research studies in non-elite settings. Furthermore, the inherent challenges of undertaking research in an international elite setting means that there is a paucity of heat acclimation research in such an applied context. As such, Study Five provided novel evidence for the efficacy of a practical, and ecologically valid, mixed-methods heat acclimation protocol within an elite team's training program.

We demonstrated that the integration of one week of such a heat acclimation protocol elicited some typical physiological, perceptual, and performance adaptations, with an additional week eliciting further thermoregulatory, sudomotor, and performance improvements in elite male athletes. Furthermore, it was demonstrated that these adaptations were well-retained after 16-days with no additional environmental heat exposure. For practitioners aiming to appropriately place heat acclimation into their pre-competition schedule, the temporal pattern of adaptation decay is an important consideration. Much of the current evidence suggests that physiological, perceptual, and performance changes can be well-retained across the following ~14 days after the heat stimulus is removed (Daanen et al., 2018; Duvnjak-Zaknich et al., 2019); however, there is a paucity of evidence regarding heat acclimation adaptation retention in an elite team sport context. Recent evidence demonstrated that most of the physiological adaptations acquired during an initial 10-day (controlled hypothermia) heat acclimation protocol were retained during a 28-day decay period in habitually trained individuals (Gerrett et al., 2021). Moreover, Pryor and colleagues (2019b) recently demonstrated the benefits of including exercise heat exposures every fifth day for 25 days, combined with regular intense physical activity during the decay period (i.e. normal training in an elite team sport context). The authors demonstrated that such a protocol acted to sustain T_c and heart rate adaptations, along with producing reduced perceptual and physiological strain during exercise heat stress one month after the completion of an initial ~10-day heat acclimation period. Given these recent findings, and the previous suggestions that fitter individuals acclimate fast, decay slow, and rapidly reacclimate (Pandolf et al., 1977), it is likely that the adaptations demonstrated in the current study would have been retained for a longer period. Unfortunately, due to constraints regarding concurrent training and competition for the elite team involved in Study Four, we were unable to assess adaptation decay for a longer period. Nonetheless, considering the paucity of data concerning heat acclimation decay in an elite context, the novel findings of Study Four have distinct implications for practitioners aiming to schedule heat acclimation into the pre-competition period. Furthermore, given the current global constraints on travel, these findings are likely to be of particular interest to practitioners who have limited access to hot environments pre-competition and thus rely on the retention of adaptations attained during a heat acclimation period.

Providing that an elite team's training centre is equipped with modern facilities (such as an environmental / heat room and hot water immersion pools), the described heat acclimation framework utilises heat training methods that are practical and easy-to-administer. For example, given that heart rate is a frequently used monitoring and assessment tool in elite sport, heart rate-controlled heat acclimation has the benefit of familiarity and ease of use in an applied sport setting, making the current heat acclimation protocol likely to be generalisable to other invasion team sports, and/or sports that include similar weekly training models. However, the experimental interpretations of controlled heart rate heat acclimation have been recently discussed by Taylor and colleagues (2020), with the authors suggesting that focussing upon physiologically-controlled (i.e. heart rate), rather than homeostatic-regulated variables (i.e. core temperature), represents an experimental simplification with clear, and sometimes unanticipated and undesirable consequences. Namely, as a physiologically controlled variable, heart rate can change quickly and extensively, depending on the stability of other physiologically regulated variables (i.e., cardiac output).

In response to this discussion of Taylor and colleagues (2020), Study Four demonstrated that athletes were able to maintain a constant relative intensity across each heat training session, exhibited via the lack of change in RPE and thermal comfort, and only small changes in TS between active heat acclimation sessions. Furthermore, progression was indicated as athletes were able to produce greater external workload during active heat acclimation sessions on Week Two, which is in line with controlled-hyperthermia heat acclimation protocols. This relationship was also recently demonstrated by Travers et al. (2020), whereby maintaining a heart rate equivalent to 65% $\dot{V}O_{2max}$ during 10 days of heat acclimation, resulted in a progressive increase in work rate across the heat acclimation protocol. Furthermore, the authors demonstrated that a similar daily T_c was achieved and maintained (~38.5 °C) during the final 60 min of each heat acclimation session (90 min), suggesting that heart rate controlled heat acclimation can provide a similar thermal impulse to controlled-hyperthermia heat acclimation, while also providing a greater and more consistent cardiovascular stimulus (Périard et al., 2021; Travers et al., 2020). Factors such as environmental conditions and dehydration can affect the cardiovascular and thermoregulatory responses during exercise in the heat. As such, when utilising controlled heart rate heat acclimation, practitioners must be aware of these influences on heart rate (and thus work rate) and be willing to control them accordingly. The current research demonstrates the first to our knowledge that utilises controlled heart rate heat acclimation methods in an elite team sport context. Further research is needed to fully understand how changing the experimental conditions during controlled heart-rate heat acclimation (e.g., environmental conditions, target heart rate, training status, and sex) may impact upon the adaptive response resulting from such heat acclimation methodologies.

In a similar manner to Chapter Six, Chapter Seven (Study Five) aimed to investigate the effectiveness and retention of a passive heat acclimation protocol, integrated within a female Olympic rugby sevens team training program. It was demonstrated that meaningful changes in resting and submaximal T_{Tymp} were achieved only after the full 10-day heat acclimation protocol was completed; however, in contrast to the persistence observed in the male athletes, these adaptations were not well-retained after 15 days of normal training, without any further heat environmental heat stimulus. No sudomotor or cardiovascular changes were apparent during or post heat acclimation. Concurrently, meaningful performance increases in repeated-sprint peak power output were evident at both mid- and post- heat acclimation, and were retained after 15 days of normal training, without any further environmental heat stimulus. These findings were particularly novel, considering the lack of practical and applied heat acclimation research in elite female populations.

The decay profile exhibited in Study Five was somewhat different to that demonstrated in Study Four. Study Five had some key differences to Study Four that may have contributed to these observations; the heat acclimation protocol in Study Five included a smaller cumulative thermal impulse than Study Four (predominantly passive heat acclimation sessions); all HWI sessions during Study Four were self-directed, thus, experimental control was not possible (despite thorough explanation of correct protocols, and the provision of temperature and perception monitoring equipment); and finally, disparities in thermal stress related to sex differences have previously been described as being responsible for the longer general temporal pattern of adaptation in females compared to males (Kirby et al., 2019; Mee et al., 2015). As such, we postulate that although the heat acclimation protocol in Study Five provided a thermal impulse to elicit transient adaptations in T_{Tymp}, a greater thermal impulse would have elicited more robust adaptations.

As previously demonstrated by Mee and colleagues (2018), 'topping up' heat exposure sessions may be necessary to elicit a similar temporal pattern of adaptations for females compared to males. Furthermore, the prescription of small weekly (1-3 days) 'top-up' heat impulses during the decay period would likely result in greater adaptation retention (Casadio et al., 2016; Weller et al., 2007). These approaches to 'topping up' heat exposure sessions during both the heat acclimation and decay periods are important considerations for practitioners when designing a heat acclimation protocol for female athletes. Consequently, the investigation of such approaches requires exploration in future research. Furthermore, it should be recognised that the athlete group studied within the current thesis are elite, whereas much of the limited published research are with recreational and are sub-elite athletes. These differences in training status may result in alterations in the profile of induction and retention of heat adaptations (Daanen et al., 2018).

An important consideration in research concerning female athletes are fluctuations in hormones associated with the menstrual cycle and/or oral contraceptive use, which can alter thermoregulatory responses and confound findings amongst females (Baker et al., 2020; Lei et al., 2019). Previous research has indicated that menstrual cycle phase and oral contraceptive use do not seem to impact thermoregulatory variables such as metabolic heat production, heat loss, or thermoeffector sensitivity during fixed or self-paced exercise in the heat (Notley et al., 2019). As such, it seems that when behavioural thermoregulation is accounted for (via the use of self-pacing protocols) menstrual phase does not affect heat-stress tolerance or performance (Lei et al., 2017). However, it remains undisputed that increases in progesterone during the luteal phase has been shown to increase the T_c setpoint by ~0.3 to 0.5 °C (Baker et al., 2020). This increase in T_c setpoint is also mimicked in the active phase, and continues into the placebo phase of OCP use (Baker et al., 2001). While speculative due to a lack of supporting evidence, performing heat acclimation during times of higher baseline T_c (e.g., in the luteal phase) may act to provide a similar T_c 'top-up' to other previously described methods.

Besides heat acclimation, the other main component of successful heat management is the incorporation of appropriate cooling strategies before, during, and after an exercise performance in the heat. As such, Chapter Eight (Study Six) aimed to investigate the effectiveness of the combined use of ice slurry ingestion and the application of ice towels to the head and neck before and during a rugby sevens specific heat response test in a controlled environment. It was demonstrated that the combined use of internal and external pre- and per-cooling strategies were effective at blunting the physiological and perceptual heat stress associated with exercising in the heat, along with contributing to practically important increases in self-paced high intensity exercise performance. As previously acknowledged, despite the currently employed internal and external cooling strategies being similar to those suggested as most beneficial in the meta-analysis of Douzi and colleagues (2019), it is unknown whether other cooling methodologies would have resulted in similar demonstrated effects. As an example (even though it was undertaken in recreationally-trained participants), Appendix One **Error!**

Reference source not found.demonstrates the utilisation of cold-water arm immersion (CWAI) during a repeated-sprint protocol designed to replicate the physiological demands of rugby sevens. In this study it was demonstrated that CWAI was effective at improving the T_{Tymp} and perceptual responses to repeated maximal efforts in the heat, along with eliciting marginal gains in performance immediately after half-time. Such a CWAI strategy demonstrates a practical pre- and/or per-cooling strategy for athletes competing in a hot and humid environment, which may be particularly relevant to athletes with minimal time to conduct other more common cooling methods.

Further demonstrating that 'any cooling may be better that no cooling', recent research demonstrated that the application of an ice vest before and during the warm-up to a rugby sevens game can limit excess rises in T_c and favourable alterations in thermal perception, without adverse effects on thermal perceptions or performance measures in both male (Taylor et al., 2019a) and female (Henderson et al., 2021) elite rugby sevens athletes. Notably, combining internal and external cooling may act to provide an increased heat storage capacity, alongside a reduced rate of heat storage during exercise (James et al., 2015; Sawka et al., 2012); hence, given our current findings, we suggest that combining internal and external cooling are likely to result in favourable alterations in thermal perception and performance. With ample information available regarding the efficacy of myriad cooling strategies for various uses (Bongers et al., 2017; Cao et al., 2022; Douzi et al., 2019; Douzi et al., 2020; Tyler et al., 2015), it seems that a best-practise cooling strategy may simply involve practitioners applying any cooling method (or combination of methods) that fit within the specific constraints of their athletic performance or event.

The current thesis clearly indicates the physiological, perceptual, and performance benefits during exercise in the heat of undertaking heat acclimation and cooling in isolation; however, to our knowledge only one study has investigated whether the application of peripheral cooling provides any benefit, over and above the benefits of heat acclimation (Adams et al., 2017). In that study, Adams and colleagues (2017) showed that hand cooling provided a greater cooling rate compared to no cooling when recreationally active males were non heat acclimated; however, hand cooling showed no additional benefits once participants were heat acclimated. Furthermore, while heat acclimation did not enhance the efficacy of such small-surface area peripheral cooling methods, heat acclimation did improve passive cooling rates when not utilising any form of cooling. While such results provide supportive evidence of the heat dissipation potential of small surface area, peripheral cooling strategies, and heat acclimation, it remains unknown whether the application of cooling to elite team sport athletes would provide any benefit, over and above the benefits of heat acclimation. Given the small beneficial changes demonstrated as a result of internal and external cooling methods in Study Six of the current thesis (e.g., increased 4-min cycling TT power output by 7 ± 33 W; ~3%), we postulate that such methods may not be beneficial in a heat acclimated elite population, due to the already high level of cardiovascular and sudomotor functions that highly-trained athletes possess. Such phenomena should be investigated in future research.

Given the well-described physiological, perceptual, and performance benefits of heat acclimation, it is strongly recommended to practitioners that individuals prioritise heat acclimation before competing in hot and/or humid environmental conditions. However, given the current global travel restrictions due to the novel coronavirus pandemic, factors such as geographical location, time of year, and access to resources may limit the capacity of elite teams to heat acclimate. In such circumstances, non-heat acclimated individuals could benefit from the use of sport-specific and practical cooling strategies. Future research should endeavour to investigate whether more intense cooling strategies (i.e., cold-water immersion, combined with ice slushy ingestion and/or the application of ice vests during non-competition exercise) can elicit beneficial responses, over and above that of heat acclimation.

9.3 Practical applications

The following practical applications are based on the outcomes of the six experimental studies within the thesis.

- Acute heat stress can have a detrimental impact on simulated physical performance in non-heat acclimated international rugby sevens athletes. With many major rugby sevens events worldwide being held in thermally challenging environments, practitioners should incorporate a sports-specific heat acclimation period into their concurrent training during preparation for competition in the heat. By doing so, beneficial physiological, perceptual, and performance changes can be elicited.
- Characterisation of the thermal stress experienced by an elite team of athletes in both competition and laboratory conditions allows practitioners to prepare individualised heat management strategies.

- To reduce the thermal load during a rugby sevens tournament, practitioners and athletes should be prepared to adjust non-competition exercise (i.e., primers, warm-ups) when competing in challenging environmental conditions. Furthermore, given the demonstrated relationship between external load variables and increases in T_c, commonly measured external load data could be useful to monitor heat exposure and performance decrement risk in real-time. Such individualised monitoring will allow for individualised recovery protocols during repeated performances across a rugby sevens tournament.

- When using practical and portable temperature measurement devices, practitioner, and athlete familiarity (for example with tympanic membrane location) will lead to greater measurement validity.
- Cycling-based training in the heat can replicate the perceptual stress of similar running exercise in the heat, giving the benefit of conserving running load for specific training; however, the physiological heat stress whilst running is greater. Practitioners working with running team sport athletes should be aware of this when designing and assessing heat acclimation protocols. When using cycling as an exercise heat stress, methods to exacerbate the thermal impulse should be considered, such as increasing exercise time/intensity or including 'thermal pre-loading' using passive methods.
- Short-term, and/or low thermal impulse acclimation protocols (i.e., Study Five) did not induce complete heat acclimation adaptations in the current thesis (no sudomotor or cardiovascular changes were apparent during or post heat acclimation); however, such low intensity, passive heat acclimation protocols can elicit meaningful changes in T_{Tymp} and performance. Such protocols allow for other training priorities to take precedence, demonstrating a practically useful heat acclimation protocol for elite team sport.
- The combined use of internal and external pre- and per-cooling strategies are effective at blunting the physiological and perceptual heat stress associated with exercising in the heat, along with contributing to practically important increases in self-paced high intensity exercise performance.

- While the importance for practitioners to include practical cooling strategies within a game-day program is undisputed, the small enhancements observed indicate that the larger performance benefits of heat acclimation must not be ignored.

9.4 Limitations

The findings and outcomes presented in the current thesis have direct and practical outcomes for the implementation of heat management strategies within an elite rugby sevens context. Whilst each experimental study has acknowledged its own specific limitations within the text of that chapter, the general limitations are noted below.

The elite athlete population in the current thesis allows for unique and ecologically valid findings; however, the caveat of undertaking research in such an elite environment is the challenge of proving these findings against an ecologically relevant control condition. As such, without the use of a control group in any of the experimental studies within this thesis, we cannot disqualify that the current findings are not due (in part) to general training adaptations. Nonetheless, it is unlikely that any meaningful non heat acclimation specific training adaptation occurred during this time, due to the calibre and training status of athletes involved in the study (Lorenzo et al., 2010). In addition, the adaptation retention profiles of Study Four and Five argue against any training effect per se, given that Study Four involved a large initial thermal impulse with high adaptation retention, while Study Five involved a smaller thermal impulse, with poor adaptation retention. As the heat response test was identical in both studies, it could be postulated that the temporal pattern of heat acclimation adaptation and decay was a result of the thermal stimulus during the heat acclimation period.

The design of many of the studies within the thesis is limited by the concurrent training periodisation, whereby training the training phase and/or parallel training stimulus could not be controlled week to week. Such limitations have previously been within elite sport contexts (Casadio et al., 2016; Pethick et al., 2018). In such circumstances, previous research has reported concurrent training load during a heat acclimation period; however, in the current thesis this was not possible due to data sharing restrictions imposed by the New Zealand Rugby Union.

A further limitation of having limited control over concurrent training is that closely controlling for menstrual cycle status is not realistic within the constraints of a professional sporting context. However, as demonstrated in the analysis of Study Six menstrual status and/or contraceptive status can be reported and accounted for in the analysis, which should be the minimal expectation in female specific future research. This may reduce variability in experiments and aid researchers in detecting differences between treatments or groups, including in measurements of T_c.

If it was possible to undertake additional heat response testing throughout the decay periods of Study Four and Five, it would have been interesting to ascertain further detail regarding the temporal pattern of adaptation retention. For example, an additional test after approximately one month without any further environmental heat stimulus would have provided practitioners with further information regarding heat acclimation periodisation within the pre-competition period. The aim of such information would be to allow practitioners to match the anticipated decay length to tapering and travel periods pre-competition. Moreover, the assessment of practical re-acclimation strategies would further aid such pre-competition periodisation.

While the current thesis demonstrates the validity of the Braun ThermoScan® 7 tympanic temperature monitoring device, it would have been preferable to use assess T_c using gold-standard methods (rectal or gastrointestinal temperature) during Studies Three, Five, and Six. However, logistical, practical, and athlete acceptance constraints precluded such use in these investigations. Similarly, Study Three indicated poor validity of a portable infrared device to measure skin temperature. As such, we made the decision not to assess skin temperature during any of the other studies within the current thesis.

Assessment of skin temperature would have provided important information regarding core to skin temperature gradients, which can be an important consideration when planning the timing of cooling strategies to best increase heat storage capacity (James et al., 2015).

While not within the scope of the current thesis, the assessment of how acute heat stress, heat acclimation, and cooling strategies can impact technical and/or tactical factors involved in rugby sevens performance would be an interesting consideration for practitioners. In turn, quantifying any psychological impact of undertaking heat acclimation and cooling strategies before and during competition may provide practitioners with a more holistic view of how heat management strategies can be beneficial for performance.

9.5 Future directions

From the outcomes and results presented within this thesis, the following key areas for future research are suggested.

- With continual advances in technology, future research should continue to evaluate new portable temperature measurement technologies against gold standards during exercise and recovery from exercise in the heat, particularly in applied sport contexts. In this way, the recent exploration of T_c predictors into complex algorithms, such as that demonstrated by Laxminarayan et al. (2018) and Moyen et al. (2021) likely have vast practical application, if indeed these are proven to be valid and reliable in elite field-based settings.

- Most importantly, future research should test re-acclimation protocols ~3 weeks after the completion of a practical and integrated heat acclimation protocol, similar to those demonstrated within this thesis. Appropriate evidence of practical re-acclimation strategies will provide further information to practitioners to support heat acclimation periodisation within a pre-competition schedule.

- In Study Three, physiological, perceptual, and performance adaptations were well-retained after 16-days with no additional environmental heat exposure. While this finding was novel, we were unaware what level of retention would have been elicited after only five days of mixed active/passive heat acclimation. Considering the favourable adaptations demonstrated after five days of heat acclimation in Study Three, future research should investigate the retention of adaptations following short-term, mixed methods heat acclimation in an elite team sport context.

- Characterisations of T_c, and predictors of T_c within elite rugby sevens competitions, should be performed across multiple match days, tournaments, and teams, providing greater statistical power, and limiting the variance due to technical and/or tactical game influences. Furthermore, practitioners with access to historical external load, technical/tactical performance, and environmental data, could perform an analysis to investigate any performance trends, based on competitions played in either temperate or hot conditions. In the same way, given that video analysis is common in an elite rugby sevens environment, future research could assess how on-field decision making and skill execution vary with and without heat acclimation during competition in hot and humid conditions.

- Undertaking heat acclimation can provide important individualised information to practitioners, particularly regarding sudomotor function. As such, given the well-defined relationship between hydration and exercise performance in the heat, tailoring hydration (and nutrition) support to such individualised requirements should be explored in future research in an elite population to maximise the cardiovascular and performance benefits of heat acclimation.

- The investigation of similar practical cooling strategies as demonstrated in this thesis should be examined within an elite heat acclimated population. Such investigations will provide practitioners with important quantification of the benefits of cooling strategies, over and above that of heat acclimation.

- Thermal impulse is mentioned throughout the current thesis; however, it was never actually measured due to constraints on continual temperature monitoring throughout the heat acclimation protocols. With large variation in the thermal stimuli among heat acclimation literature (session duration, days of heat acclimation protocol, mode of heat acclimation stimulus etc) the monitoring of cumulative thermal impulse across a heat acclimation protocol should be considered in future research. In this way, the application of portable continual temperature measurement systems [such as the Kenzen™ solution (Moyen et al., 2021)] may prove useful. Ultimately, the aim of such description should be to objectively identify thermal impulse profiles that are required to elicit different patterns of thermoregulatory adaptations.

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Chapter Ten Appendices

Appendix One Presented abstracts

Heat response testing in elite rugby sevens athletes; An eye to Tokyo 2020

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Presented at Sport and Exercise Science New Zealand Conference (2018), Dunedin, New Zealand.

Little is known about the physiological and perceptual responses of elite rugby sevens athletes to the heat stress expected in at the 2020 Tokyo Olympics.

Seven elite male rugby sevens athletes completed a heat response test (HRT) consisting of a 15-min warm up, simulated sevens game and 1.2 km time trial (TT) on a treadmill in ambient (AMB; 20 °C, 50% RH) and Tokyo (HOT; 35 °C, 80% RH) conditions. Tympanic temperature (T_{Tymp}), heart rate (HR), rate of perceived exertion (RPE), thermal sensation (TS), thermal comfort (TC) and thirst were measured at baseline, half time, and pre-TT.

T_{Tymp} and HR during HOT were significantly greater at half-time (1.4 ± 0.7 °C; 19 ± 15 bpm) and pre-TT (1.6 ± 0.7 °C; 25 ± 16 bpm) compared to AMB (all mean ± 95% CI; *$p<0.05$)*. T_{Tymp} and HR were not different at baseline. TS, TC and RPE during HOT were greater at all timepoints (all ES > 1.2), whereas thirst was only greater pre-TT (ES = 1.2). Mean (± SD) time to complete the TT was greater in HOT (5.58 ± 0.83 min) compared to AMB (4.43 ± 0.27 min; ES = 1.8).

Simulated environmental conditions expected during the 2020 Tokyo Olympics can impact physiological, perceptual and performance markers during a rugby sevens specific HRT.

Characterisation of core temperature response to an international rugby sevens tournament played in hot and humid conditions.

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Presented at Sport and Exercise Science New Zealand Conference (2019), Palmerston North, New Zealand.

Rugby sevens is a high intensity contact sport, typically with 5-6 games across two days. Previously it has been shown that there are game on game increases in core temperature (T_c) during tournaments, however, this has not been documented in an environment similar to that expected at the Tokyo 2020 Olympic games.

T_c was collected using ingestible telemetry pills in twelve male non heat-acclimated international elite rugby sevens athletes, during a two-day tournament in Suva, Fiji. Cooling strategy use and environmental conditions were also measured.

Mean peak game T_c in games 1 -5 was 38.9 ± 0.5 ˚C; 38.9 ± 0.6 ˚C; 38.8 ± 0.4 ˚C; 39.1 ± 0.5 ˚C; 39.1 ± 0.3 ˚C. During the final game (game 5) six athletes exhibited peak game T_c over 39.0 ˚C. No pre or per cooling methods were used by any of the athletes. Voluntary post-game cold water immersion was used minimally by athletes. Mean game temperature was 29.3 ± 1.8 ˚C with 75 ± 3 % relative humidity.

Given that temperatures over 39.0 ˚C have been associated with reduced repeated sprint ability, heat acclimating prior to competition in hot environments, along with including common place pre and per cooling strategies may help to limit the rise in core temperatures seen in the current study.

Competing in rugby sevens on a hot and humid climate without heat acclimation or cooling strategies can result core temperatures that are likely to influence performance.

Beat the heat: The effectiveness of a practical, cold water arm immersion protocol during a simulated rugby sevens protocol.

[1,2,3]***Fenemor*, *S P.*** [1]*Walsh, K.* [1]*Davie, C.* [1]*Wharemate, J.* [1]*van der Laan, M.* [1]*Carson, D.* [1]*Olsen, J.* [1]*Beaven, C M.*

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The environmental conditions at the Tokyo 2020 Olympics are likely to decrease performance factors associated with rugby sevens. The efficacy of many cooling strategies has been well described, however, practical strategies such as pre- and per-cooling using cold-water immersion of the arms (CWAI) has received little consideration.

Nine participants completed two WattBike™ repeated-sprint interventions using a cross-over design in a heated laboratory environment (~30 ˚C, ~50 % RH). The protocol was designed to replicate the physiological demands of rugby sevens. Tympanic temperature (T_{TYMP}), peak power (PP), and thermal comfort was collected before, during, and after each intervention. Participants either performed CWAI with arms submerged to the elbow in ice water for 60 seconds both after the warm-up and during half-time, or a passive control.

CWAI enhanced PP immediately post half-time by 96 W ($p=0.01$, Cohen's $d=0.61$), with no significant differences at any other time point. T_{TYMP} was decreased at all time points after half-time. Thermal comfort was significantly improved only immediately post each immersion ($p<0.05$).

Given that the CWAI intervention was transiently effective in enhancing PP and thermal comfort, and decreasing T_{TYMP}, it may provide a practical pre- &/or per-cooling strategy for athletes competing in hot and humid environments. Effective cooling may also positively impact subsequent rugby sevens performance by mitigating the increase in T_{TYMP}.

A cold-water arm immersion protocol can improve performance, T_{TYMP}, and perceptual measures when completing repeated efforts in the heat.

Cold-water immersion of the arms as a cooling strategy during repeated sprint exercise.

[1,2]Fenemor, S; [1]Beaven, C. M.
[1]University of Waikato; [2]High Performance Sport New Zealand

Presented at Sport and Exercise Science New Zealand Conference (2020), Christchurch, New Zealand.

Full-body cold-water immersion is the best method of core heat conduction, however, practical strategies such as using cold-water immersion of the arms (CWAI) has received little consideration.

Fifteen non heat-acclimated, recreationally trained participants (5 male) completed two WattBike™ repeated sprint interventions using a randomised cross-over design in a heated laboratory environment (~30-32˚C, ~55-65% RH). The protocol consisted of a 19-min controlled intensity warm-up, followed by two 7-min halves (H1, H2) designed to replicate the physiological demands of rugby sevens, whereby participants completed six 6s maximal effort sprints per half. Participants either performed CWAI for 60s after the warm-up and during half-time, or a passive control. Tympanic temperature (T_{TYMP}), heart rate (HR), perceived exertion (RPE), thermal sensation (TS), thermal comfort (TC), peak power (PPO) and mean power output (MPO) were collected throughout each test.

CWAI decreased T_{TYMP} during H2 ($p< 0.01$, $d= -0.59 \pm0.34$), while CWAI decreased TS during H1 ($p< 0.01$, $d= -0.55 \pm0.32$) and H2 ($p= 0.06$, $d= -0.36 \pm0.31$) and improved TC during H2 ($p= 0.05$, $d= -0.36 \pm0.31$). In the first sprint after half-time, both MPO and PPO were greater in CWAI (43 W, $d= 0.21 \pm0.21$; 47 W, $d= 0.21 \pm0.20$; both $p= 0.08$, respectively). There were no differences in HR or RPE between CWAI and control at any measurement point.

CWAI was effective at improving the T_{TYMP} and perceptual response to repeated maximal efforts in the heat, along with marginal gains in performance immediately after half-time. This may provide a practical pre- and/or per-cooling strategy for athletes competing in a hot/humid environment, which may be particularly relevant to athletes with minimal time to conduct other more common cooling methods.

Appendix Two Co-authorship forms

Co-Authorship Form

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter Three

Fenemor, S. P., Gill, N. D., Sims, S. T., Beaven, C. M., & Driller, M. W. (2020). Validity of a tympanic thermometer and thermal imaging camera for measuring core and skin temperature during exercise in the heat. *Measurement in Physical Education and Exercise Science, 24*(1), 49-55. https://doi.org/10.1080/1091367X.2019.1667361

Nature of contribution by PhD candidate	Collected data; analysed data; wrote first manuscript draft; wrote and submitted final manuscript
Extent of contribution by PhD candidate (%)	80%

CO-AUTHORS

Name	Nature of Contribution
Gill, N. D,	Contributed to manuscript drafting
Sims, S. T.	Contributed to manuscript drafting and ethics approvals
Beaven, C. M.,	Contributed to data collection and manuscript drafting
Driller, M. W.	Contributed to data collection, data analysis, and manuscript drafting

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Gill, N. D.	[signature]	28/03/22
Sims, S. T.	[signature]	30/03/22
Beaven, C. M.	[signature]	30/03/22
Driller, M. W.	[signature]	28/03/22

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Chapter Four
Fenemor, S. P., Gill, N. D., Driller, M. W., Mills, B., Casadio, J. R., & Beaven, C. M. (2021). The relationship between physiological and performance variables during a hot/humid international rugby sevens tournament. *European Journal of Sport Science*, 1-9. https://doi.org/10.1080/17461391.2021.1973111

Nature of contribution by PhD candidate	Designed study; Collected data; analysed data; wrote first manuscript draft; wrote and submitted final manuscript
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
Gill, N. D,	Contributed to study design manuscript drafting
Driller, M. W	Contributed to study design manuscript drafting
Mills, B.,	Contributed to data collection
Casadio, J. R.,	Contributed to manuscript drafting
Beaven, C. M.,	Contributed to study design, data analysis, and manuscript drafting

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Casadio, J. R.,	[signature]	24/03/22
Beaven, C. M.,	[signature]	30/03/22

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Chapter Five
Fenemor, S. P., Gill, N. D., Driller, M. W., Mills, B., Sella, F., Black, K & Beaven, C. M. (2022). Evaluation of an off-feet heat response test for elite rugby sevens athletes. *Science and Sport*. **In press**

Nature of contribution by PhD candidate	Designed study; Collected data; analysed data; wrote first manuscript draft; wrote and submitted final manuscript
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
Gill, N. D,	Contributed to study design, data collection, and manuscript drafting
Driller, M. W	Contributed to study design and manuscript drafting
Mills, B.,	Contributed to data collection
Sella, F.,	Contributed to data collection
Black, K	Contributed to data analysis
Beaven, C. M.	Contributed to study design, data collection, and manuscript drafting

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Chapter Six
Fenemor, S. P., Gill, N. D., Driller, M. W., Mills, B., Casadio, J. R., & Beaven, C. M. (2022). Practical application of a mixed active and passive heat acclimation protocol in elite male Olympic team sport athletes. *Applied Physiology, Nutrion, and Metabolism*. In review

Nature of contribution by PhD candidate	Designed study; Collected data; analysed data; wrote first manuscript draft; wrote and submitted final manuscript
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
Gill, N. D,	Contributed to study design and manuscript drafting
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Casadio, J. R.,	Contributed to study design and manuscript drafting
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Chapter Seven
Fenemor, S. P., Gill, N. D., Driller, M. W., Anderson, B., Casadio, J. R., Sims, S.T., & Beaven, C. M. (2022). Heating up to keep cool: Benefits and persistence of a practical heat acclimation in an elite female rugby sevens team. *International Journal of Sport Physiology and Performance*. In review

Nature of contribution by PhD candidate	Designed study; Collected data; analysed data; wrote first manuscript draft; wrote and submitted final manuscript
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
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Chapter Eight

Fenemor, S. P., Gill, N. D., Driller, M. W., Mills, B., Casadio, J. R., & Beaven, C. M. (2022). Evaluation of standard cooling practises in elite rugby sevens athletes. *Research Quarterly for Exercise and Sport*. In review

Nature of contribution by PhD candidate	Designed study; Collected data; analysed data; wrote first manuscript draft; wrote and submitted final manuscript
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
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Anderson, B.	Contributed to study design and data collection
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Casadio, J. R.		24/3/22
Beaven, C. M.		30/03/22

Appendix Three Ethical approvals

The University of Waikato
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Human Research Ethics Committee
Karsten Zegwaard
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THE UNIVERSITY OF WAIKATO
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31-10-2018

Stacy Sims
By email: stacy.sims@waikato.ac.nz

Stephen Fenemor
By email: sfenemor@waikato.ac.nz

Dear Stephen

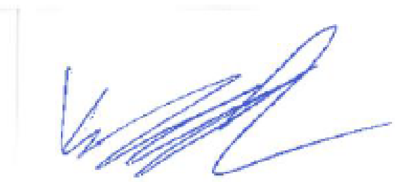
UoW HREC(Health)2016#9 : **Effects of heat, humidity and simulated altitude exposure on physiological performance during endurance exercise and resistance training**

Thank you for your request to clarify the time duration of ethics approval of an application considered by the committee.

The committee typically grants approval for a three year period.

The above application was approved in 18th of October, 2016. This means the approval remains valid until 18th of October, 2019.

Yours sincerely



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Karsten Zegwaard PhD
Acting Chairperson
University of Waikato Human Research Ethics Committee

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THE UNIVERSITY OF
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31-10-2018

Stephen Fenemor
By email: sfenemor@waikato.ac.nz

Dear Stephen

UoW HREC(Health)2018#64 : Identifying Heat Management Strategies to Enhance Training, Competition and Recovery in Male Rugby 7's Athletes

Thank you for the submission of your amended application HREC(Health)2018#64 for ethical approval and responses to queries raised by the committee.

We are now pleased to provide formal approval for your project within the parameters outlined within your application.

If you need to make any changes to the elements approved within the application that requires ethical approval, please contact with committee (humanethics@waikato.ac.nz), quoting the approval number, and seek an amendment to your application. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

Karsten Zegwaard PhD
Acting Chairperson
University of Waikato Human Research Ethics Committee

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Human Research Ethics Committee
Julie Barbour
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THE UNIVERSITY OF WAIKATO
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9 September 2019

Stephen Fenemor
By email: sfenemor@waikato.ac.nz

Dear Stephen

UoW HREC(Health)2018#64 : Identifying Heat Management Strategies to Enhance Training, Competition and Recovery in Rugby 7's Athletes – Updated Approval

Thank you for the submission of your amendment request for the study approved as HREC(Health)2018#64.

We are now pleased to provide formal approval for the requested amendments, including the addition of female participants, and minor changes to the research protocol in response to initial findings.

If you need to make any further changes to the elements approved within the application that requires ethical approval, please contact with committee (humanethics@waikato.ac.nz), quoting the approval number, and seek an amendment to your application. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

Julie Barbour PhD
Chairperson
University of Waikato Human Research Ethics Committee