OPTIMISING POST-EXERCISE COLD WATER IMMERSION PROTOCOLS: UNDERSTANDING THE IMPACT OF INDIVIDUAL BODY SIZE AND COMPOSITION

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B.App.Sci (Human Movement), Honours

Submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy (PhD)

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April 2017
Abstract

The use of cold water immersion (CWI) for post-exercise recovery has become increasingly prevalent in recent years with the aim to promote recovery following intense periods of training and competition. There is considerable variance reported with regards to the performance recovery benefits of CWI, and this is often attributed to differences in the CWI protocol (e.g. water temperature, immersion duration, immersion depth or mode of immersion), and type of exercise used (e.g. endurance vs sprint events). Individual differences may also impact this variance (e.g. age, gender, body size and composition, etc.); however, to date these factors have received little attention. This thesis aimed to examine how differences in CWI protocols and individual body size and composition may impact physiological and performance responses to post-exercise CWI. A series of three separate but related studies were conducted to further describe the physiological and performance responses to post-exercise CWI with the purpose of optimising the prescription of CWI for athletes.

Study 1 examined the effect of post-exercise CWI protocols, compared with control (CON), on the magnitude and time-course of changes in core temperature ($T_c$). Pooled data analysis using linear mixed modelling was conducted utilising the raw data obtained from 13 previously conducted studies. $T_c$ was examined in the models as a double difference ($\Delta\Delta T_c$), calculated as the change in $T_c$ in the CWI condition minus the corresponding difference under the CON condition. The effect of CWI treatment on $\Delta\Delta T_c$ was assessed using separate linear mixed models across two time components. The first component examined the change in $T_c$ between the end of exercise and the end of the CWI/CON recovery intervention (component 1: immersion). The second component examined the post-recovery change only and was defined as the difference in $T_c$ between the end of the CWI/CON recovery intervention and each of the available post-recovery time-points (component 2: post-recovery). Intermittent CWI protocols were found to result in a $\Delta\Delta T_c$ that was $0.248 \pm 0.097$ °C (estimate ± se) lower than continuous protocols during the immersion component and $0.141 \pm 0.097$ °C lower during the post-recovery component, where lower $\Delta\Delta T_c$ implies a larger decrease relative to CON. The effect of protocol mode (continuous or intermittent) was significant for the recovery component ($p = 0.022$) but not the post-recovery component ($p = 0.150$). There was a significant CWI temperature effect during the immersion component ($p = 0.050$), where a decrease in water
temperature of $1^\circ$C resulted in a decrease in $\Delta\Delta T_c$ of $0.025 \pm 0.012^\circ$C. Similarly, the effect of CWI duration was significant during the immersion component ($p = 0.009$), where every 1 min of immersion resulted in a decrease in $\Delta\Delta T_c$ of $0.018 \pm 0.006^\circ$C. The effect of CWI depth was confounded by immersion time and water temperature. Immersion time and water temperature did not have a significant effect on $\Delta\Delta T_c$ during the post-recovery component, however the time frame between the end of exercise and start of immersion was significant ($p = 0.002$). For every 1 min of time between exercise ceasing and start of immersion the $\Delta\Delta T_c$ increased by $0.011 \pm 0.004^\circ$C. During the post-recovery component, the peak difference between the CWI and CON interventions occurred at 60 min post-recovery. Variations in protocol factors such as immersion mode, water temperature, and duration had a significant effect on the extent of change in $T_c$. Therefore, careful consideration should be given to determine the optimal amount of cooling before determining which combination of protocol factors to prescribe.

Study 2 examined the influence of body composition on temperature and blood flow responses to post-exercise CWI, hot water immersion (HWI) and CON. Participants were stratified into three distinctly different body composition groups: 1) low mass and low fat (LM-LF) BMI $\leq 21.0$ kg/m$^2$ and body fat percentage $\leq 13.0$ % (n = 9); 2) high mass and low fat (HM-LF) BMI $\geq 25.0$ kg/m$^2$ and body fat percentage $\leq 13.0$ % (n = 9); or 3) high mass and high fat (HM-HF) BMI $\geq 25.0$ kg/m$^2$ and body fat percentage $\geq 18.0$ % (n = 9). It was found that during CON and HWI there were no differences in $T_c$ or muscle temperature ($T_m$) between body composition groups. The rate of fall in $T_c$ following CWI was greater in the LM-LF ($0.03 \pm 0.01^\circ$C/min) group compared to the HM-HF ($0.01 \pm 0.001^\circ$C/min) group ($p = 0.002$). $T_m$ decreased to a greater extent during CWI in the LM-LF and HM-LF groups ($8.6 \pm 3.0^\circ$C) compared with HM-HF ($5.1 \pm 2.0^\circ$C, $p < 0.05$). Blood flow responses did not differ between groups. $T_c$ and $T_m$ in response to post-exercise CWI were correlated with the body surface area to mass ratio and all measures of adiposity. Differences in body composition alter the thermal response to post-exercise CWI, which may explain some of the variance in the responses to CWI recovery. Furthermore, the results of this study provide support to the hypothesis that body surface area, relative to mass, is an important factor influencing the thermal responses to cold water immersion, in addition to the actual CWI protocol.

Study 3 expanded on the findings from Study 2 and compared the effect of CWI on thermal responses and the recovery of performance between individuals with high and low percentages of body fat. Participants were stratified into two body composition groups 1) low fat (LF), body
fat percent $\leq 12.0 \% \ (n = 10)$; or high fat (HF), body fat percent $\geq 18.0 \% \ (n = 10)$. $T_c$ and thermal sensation (TS) were significantly lower in LF compared to HF from 10 min ($T_c$: LF $36.5 \pm 0.5$, HF $37.2 \pm 0.6 ^\circ C$; TS: LF $2.3 \pm 0.5$, HF $3.0 \pm 0.7$ a.u.) to 40 min ($T_c$: LF $36.1 \pm 0.6$, HF $36.8 \pm 0.7 ^\circ C$; TS: LF $2.3 \pm 0.6$, HF $3.2 \pm 0.7$ a.u.) following CWI ($p < 0.05$). Recovery of time trial (TT) performance was significantly enhanced following CWI in HF ($10.3 \pm 6.1 \%$) compared to LF ($3.1 \pm 5.6 \%$, $p = 0.01$) however, no differences were observed between HF ($6.9 \pm 5.7 \%$) and LF ($5.4 \pm 5.2 \%$) in the CON trial. Additionally, the $T_c$ reduction which occurs during cold water immersion was found to correlate with the recovery in cycling TT performance from post-exercise to post-recovery, whereby the greater the decrement in $T_c$ the greater the decrement in TT performance. This study demonstrated that body composition influences the magnitude of the decrement in $T_c$ change during and following CWI. Additionally, CWI was found to enhance performance recovery when the decrement in $T_c$ was not excessive. Therefore, body composition should be considered when planning CWI protocols to avoid overcooling and therefore maximise performance recovery.

The results of this series of studies demonstrate that variation in the CWI protocol prescribed (particularly mode, temperature and duration of immersion) along with the variation in the individual body size and composition characteristics of the athlete will determine the extent of the thermal/physiological changes induced by post-exercise CWI. Changes in $T_c$ in response to post-exercise CWI were related to the recovery of performance and overcooling the athlete can have a negative impact on the recovery of performance. Therefore, it is important to consider both individual characteristics of the athlete and the impact of the immersion protocol prescribed in order to avoid over- or undercooling. The findings of this thesis will ideally lead to further research and ultimately the use of individualised hydrotherapy protocols, which would represent a shift in practice in the field of athlete recovery.
Declaration of Originality

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Jessica M. Stephens
13/04/2017
Acknowledgements

This thesis would not have been possible without the support and encouragement of a number of people, my sincere thanks goes out to the following people:

First and foremost, to my supervisory team, Shona Halson, Jo Miller, Chris Askew and Gary Slater. Your knowledge, support and advice over the years have been invaluable. I have learnt so much from each of you and have become a better researcher and sport scientist thanks to you. In particular, I would like to thank Shona for giving me the opportunity to come to the AIS to complete my PhD.

I’d like to acknowledge and thank the AIS and USC, the support provided to me by both institutions has been fantastic.

There are so many people at the AIS who have supported me and have been so generous with their time and assistance. In particular, I would like to thank Dale Chapman, Jamie Plowman, Nathan Versey, Graeme Allbon, Hamilton Lee, Alisa Nana and Chris Gore. I would also like to thank all of the students and scholars who have helped me over the years and made the AIS a really great place to be.

To all of the participants who volunteered for my research projects, thank you so much for all of the time you gave up to participate. Your enthusiasm and willingness to get in and do everything that was asked of you is greatly appreciated. This PhD would not have been possible without each and every one of you.

To my amazing friends Laura, Anthea and Sam, thank you so much for your proof reading assistance.

Finally, to my parents Kerry and Gary and my brother Greg, the encouragement and support that you have given me not only over the last 4 years but throughout my life means the world to me. Whenever I doubted myself you always believed in me, I could not have achieved this without you.
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<td>%BF</td>
<td>Percent body fat.</td>
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<tr>
<td>ΔΔT&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Delta-delta core temperature.</td>
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<tr>
<td>BAS</td>
<td>Baseline.</td>
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<tr>
<td>BM</td>
<td>Body mass.</td>
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<tr>
<td>BMI</td>
<td>Body mass index.</td>
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<td>BP</td>
<td>Blood pressure.</td>
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<tr>
<td>BSA</td>
<td>Body surface area.</td>
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<td>BSA:M</td>
<td>Body surface area to mass ratio.</td>
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<tr>
<td>CBV</td>
<td>Central blood volume.</td>
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<tr>
<td>CI</td>
<td>Confidence interval.</td>
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<td>CMJ BW</td>
<td>Body weight countermovement jump.</td>
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<tr>
<td>CMJ WT</td>
<td>Weighted countermovement jump.</td>
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<tr>
<td>CON</td>
<td>Control.</td>
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<tr>
<td>CV</td>
<td>Coefficient of variation.</td>
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<td>CWI</td>
<td>Cold water immersion.</td>
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<td>DXA</td>
<td>Dual energy x-ray absorptiometry.</td>
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<td>FM</td>
<td>Total body fat mass.</td>
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<tr>
<td>HF</td>
<td>High fat body composition group (Chapter 6).</td>
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<tr>
<td>HIIT</td>
<td>High intensity interval test.</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td><strong>HM-HF</strong></td>
<td>High mass, high fat body composition group (Chapter 5).</td>
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<tr>
<td><strong>HM-LF</strong></td>
<td>High mass, low fat body composition group (Chapter 5).</td>
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<tr>
<td><strong>HR</strong></td>
<td>Heart rate.</td>
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<td><strong>HWI</strong></td>
<td>Hot water immersion.</td>
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<tr>
<td><strong>IMTP</strong></td>
<td>Isometric mid-thigh pull.</td>
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<tr>
<td><strong>ISAK</strong></td>
<td>International society for the advancement of kinanthropometry.</td>
</tr>
<tr>
<td><strong>LF</strong></td>
<td>Low fat body composition group (Chapter 6).</td>
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<tr>
<td><strong>LM</strong></td>
<td>Total body lean mass.</td>
</tr>
<tr>
<td><strong>LM-LF</strong></td>
<td>Low mass, low fat body composition group (Chapter 5).</td>
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<tr>
<td><strong>MVIC</strong></td>
<td>Maximal voluntary isometric contractions.</td>
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<tr>
<td><strong>PEX</strong></td>
<td>Post-exercise.</td>
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<td><strong>PPO</strong></td>
<td>Peak power output.</td>
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<tr>
<td><strong>PREC</strong></td>
<td>Post-recovery.</td>
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<td><strong>Q</strong></td>
<td>Cardiac output.</td>
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<td><strong>REC</strong></td>
<td>Recovery.</td>
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<td><strong>RPE</strong></td>
<td>Rating of perceived exertion.</td>
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<td><strong>SD</strong></td>
<td>Standard deviation.</td>
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<tr>
<td><strong>SE</strong></td>
<td>Standard error.</td>
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<tr>
<td><strong>SSC</strong></td>
<td>Stretch shortening cycle.</td>
</tr>
<tr>
<td><strong>Sum7</strong></td>
<td>Sum of seven skinfolds.</td>
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<tr>
<td><strong>SV</strong></td>
<td>Stroke volume.</td>
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\( T_c \)  
Core temperature.

\( T_m \)  
Muscle temperature.

\( TQR \)  
Total quality recovery.

\( TS \)  
Thermal Sensation.

\( Tsk \)  
Skin temperature.

\( TT \)  
Time trial.

\( TWI \)  
Thermoneutral water immersion.

\( VO_{2\max} \)  
Maximal oxygen uptake.

\( W \)  
Watts.
List of Original Publications

Peer review publications arising directly from this thesis:


Peer reviewed abstracts from this thesis:


Additional publications arising during the candidature process:


1.1 Background

Elite athletes face gruelling demands from their training and competition schedules, which can place significant stress on the athlete, potentially compromising their ability to optimally train and/or perform. Maintaining an optimal balance between stress and recovery helps ensure athletes are able to perform optimally, if an imbalance occurs the risk of overtraining, injury, or illness increases. A number of recovery modalities are employed by athletes in an attempt to accelerate the recovery process, including but not limited to, active recovery, stretching, massage, sleep, compression, nutrition and hydrotherapy. Hydrotherapy interventions such as cold water immersion (CWI), hot water immersion (HWI) and contrast water therapy have become a popular part of an athlete’s recovery regimen. CWI in particular has become one of the most frequently utilised recovery modalities and in recent years the quantity of research investigating the efficacy of CWI has increased.

Whilst there has been an increase in the research examining CWI, there is still a lack of knowledge regarding the physiological responses underpinning the benefit/s of hydrotherapy. A greater understanding of the physiological responses induced by CWI will enhance current knowledge and allow improved prescription in order to optimise performance outcomes. While research to date has generally shown CWI to have a positive effect on enhancing the recovery of performance, there are a number of studies which have shown CWI to have either a negligible or a detrimental effect on the recovery of performance. Positive findings include those from cycling studies which have shown that the total amount of work performed or time taken in a trial time (TT) has been maintained and sprint and TT performance over multiple days enhanced when CWI was implemented for recovery. Additionally, CWI following team sport or simulated team sport performance has been shown to reduce the decrement in sprint speed, countermovement jump height, strength, acceleration and total distance covered during a football game. Muscle damaging exercise studies have shown that CWI enhances the recovery of muscle force, neuromuscular performance, squat jump performance and isometric squat performance. Despite these positive findings, some studies have observed CWI to have no effect on the recovery of cycling TT or sprint
performance and no effect on performance recovery following muscle damaging exercise or soccer. Furthermore, there have been a small number of studies that have shown CWI to have a negative effect on performance recovery by reducing peak power, average power, maximal isometric torque and total work in cycling as well as reducing sprint performance after a game of rugby.

It is postulated that this variability in performance recovery is largely due to CWI protocol variation and/or individual differences. Indeed, a lack of understanding regarding how best to utilise CWI remains. To date, the CWI protocols investigated in research are variable and parameters such as the duration, depth, temperature and mode of immersion (continuous vs intermittent) are diverse and based on current practice rather than scientific knowledge. Variability in the CWI protocol utilised is thought to impact physiological and performance recovery predominantly through the dose of cooling which is provided. Different combinations of these protocol parameters will lead to a different dose of cooling applied and it is unknown how these factors interact and what the optimal combination of factors is. It is also unknown what dose of cooling is optimal for performance recovery.

In addition to CWI protocols, differences in body size and composition may also contribute to the variability observed in previous research. Body composition has the potential to influence the degree of physiological changes individual athlete’s exhibit in response to CWI. The body achieves thermal insulation from a combination of skin, subcutaneous fat and muscle with each of these tissues providing a different amount of resistance to thermal stress. Overall, athletes have a diverse range of body compositions depending on their sporting speciality and differing amounts of each of the aforementioned tissue types, resulting in different time-courses of thermal change in response to CWI. Indeed, when the effect of low, average and high calf skinfold thickness on gastrocnemius muscle temperature was examined, it was found that that the amount of subcutaneous fat over the cooling site affected both the total temperature change and the rate of change during ice pack application. Muscle mass has also been found to significantly contribute to total body insulation during water immersion, with previous research observing that approximately 80% of total body insulation comes from muscle mass. Both subcutaneous fat and muscle mass have been independently shown to have an impact on thermal responses. Therefore, it is important to conduct further research to better understand how differences in these body composition variables impact upon temperature and blood flow.
responses and possible interactions. This will enable CWI protocols to be prescribed specifically to individual athletes, reducing the risk of negatively influencing performance.

The mixed findings previously highlighted have led to a lack of consensus amongst sport science professionals as to the effectiveness of CWI and/or the best protocols (i.e. temperature, immersion depth, time, etc.) to utilise, which may be confusing for coaches and athletes. Providing optimal individualised protocols will ensure that the athletes will maximise recovery without jeopardising subsequent performance. Therefore, this PhD intended to provide clarity to sport science professionals, athletes, and coaches regarding the effective utilisation of CWI.

1.2 PhD Aims

To date, CWI research has shown mixed results for the recovery of performance variables. The purpose of the present series of studies was to enhance the understanding of the physiological responses induced by post-exercise CWI and the associated factors which impact these responses (CWI protocols, individual body composition). It was hypothesised that it is the interaction between the CWI protocol and the individual characteristics of the athlete which will impact the physiological changes observed and ultimately performance recovery (Figure 1.1). Therefore, this PhD attempted to address the following aims; 1) to investigate and outline the physiological responses to CWI, 2) to understand the impact of variation in CWI protocols, 3) to understand the implications of individual body size and composition characteristics on the physiological responses and 4) to optimise CWI protocol prescription for individual athletes.
1.3 Study aims

This thesis attempted to address the following specific aims:

**Study One (Chapter Four)**

**Title:** Impact of variations in cold water immersion recovery protocols on core temperature change determined by pooled data analysis.

1. To determine the impact of protocol variation (temperature, duration, depth and mode) on core temperature ($T_c$) responses to post-exercise CWI.

2. To characterise the time-course of $T_c$ responses to post-exercise CWI compared to control (CON).

**Study Two (Chapter Five)**

**Title:** Effect of body size and composition on temperature and blood flow responses to post-exercise hydrotherapy.

1. To compare the effect of CWI, HWI and CON on body temperature and limb blood flow responses following exercise.
2. To compare physiological responses following recovery (CWI, HWI, CON) between three distinctly different body composition groups and examine the time-course of these changes.

3. Establish any relationships between body composition and physiological responses to post-exercise CWI, HWI and CON.

**Study Three (Chapter Six)**

*Title: Influence of body composition on physiological responses to cold water immersion and the recovery of exercise performance.*

1. To examine whether thermal responses to post-exercise CWI differ between high and low fat athletes.

2. To examine whether recovery of performance following post-exercise CWI differs between high and low fat athletes.

3. To identify relationships between body composition variables and changes in body temperature and/or changes in performance.
Chapter Two – Literature Review

Chapter Two includes the below publication:

**Cold water immersion for athletic recovery: one size does not fit all.**

Jessica M. Stephens\textsuperscript{1,2}, Shona Halson\textsuperscript{2}, Joanna Miller\textsuperscript{2}, Gary Slater\textsuperscript{1} and Christopher D. Askew\textsuperscript{1}

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Journal: International Journal of Sports Physiology and Performance

Invited review. 2017, Volume 12, Issue 1, Pages 2-9

Impact Factor: 3.042

**Author Contributions**

Student Contribution to work: Involved in the initial conception of the review focus, was responsible for writing the first draft of the manuscript and modified drafts based on co-author recommendations

Conceived and designed the review: JS, CA, SH, JM

Wrote/reviewed the paper: JS, CA, SH, JM, GS
2.1 Introduction

Recovery interventions have become an integral part of most elite athletes’ training programs. Adequate recovery enables physiological and psychological function to be restored, minimising the negative effects of fatigue and allowing athletes to optimally train and compete. Many strategies are currently used to hasten the recovery process such as active recovery, stretching, massage, sleep, compression and hydrotherapy. Hydrotherapy is the broad term encompassing cold water immersion (CWI), hot water immersion (HWI), contrast water therapy and thermoneutral water immersion (TWI). CWI tends to be the most popular post-exercise hydrotherapy method, and while the popularity of CWI has led to multiple studies and reviews in the area of water immersion, this research has predominantly focused on performance outcomes associated with post-exercise CWI and has found mixed results.

Previous research has demonstrated that CWI is useful for maintaining repeat performance in hot environments by reducing thermal strain and for reducing muscle soreness and aiding recovery from secondary exercise induced muscle damage, which often occurs following repetitive high intensity exercise and team sport performance. CWI has also been shown to be beneficial for enhancing perceptions of recovery. Conversely, some studies have shown CWI to elicit no benefit or to have detrimental effects on performance recovery. The disparity in results has led to much debate amongst researchers and sports science professionals as to the effectiveness of CWI and this contention highlights the importance of fully understanding reasons why CWI may or may not be effective. HWI is also commonly utilised by athletes to enhance recovery, however there has been very limited investigation into its effects on the recovery of performance. Much like CWI the findings for HWI to date have been mixed.

Hydrotherapy relies on the effect of water temperature and hydrostatic pressure to instigate a number of physiological changes that are hypothesised to underpin performance recovery. CWI leads to a redistribution of blood flow and reductions in core and tissue temperatures. There is evidence that CWI reduces thermal strain, swelling, inflammation, muscle spasm and pain. Whilst HWI has been suggested to lead to superficial vasodilation and an increase in blood flow which is hypothesised to enhance waste removal from and nutrient delivery to cells. HWI has also been shown to increase heart rate, cardiac output and tissue temperature. However, the exact thermal and cardiovascular responses to post-exercise CWI
and HWI remain to be fully elucidated. In particular, the effect of CWI and HWI on muscle temperature and blood flow requires further investigation.

The effect of CWI and HWI and the ability to understand the underlying physiological mechanism/s is determined largely by the immersion protocol utilised. Optimal protocol parameters will likely differ depending upon the outcome of interest and specific recovery needs, which are determined by the event-specific perturbations caused by prior exercise and also the time-frame available before subsequent performance is required. Current hydrotherapy protocols vary and there is a dearth of strong scientific evidence surrounding optimal duration, temperature, immersion depth and the number/frequency of immersions. CWI interventions with favourable outcomes tend to be performed in water between 10-20°C, for 5-15 min for a single immersion protocol or 1-5 min per immersion for multiple immersions.\(^{38}\) CWI performed to the level of the hips or shoulders has shown greater beneficial performance outcomes than limb only immersion.\(^{16,42}\) HWI tends to be performed in water \(\geq 36.0\,^\circ\text{C}\) for 10-24 min however there is very limited understanding on optimal protocols for HWI with no recommendations for depth or number of immersion.\(^{38}\)

Physiological responses to CWI and HWI protocols will also depend on the individual characteristics of the athlete/participant, for example their physique traits. Indeed previous thermoregulatory research has shown body composition characteristics (such as body fat, body surface area and muscle mass) do impact physiological responses to cold stress,\(^ {34}\) however there is limited knowledge on the impact of these individual differences on physiological and performance responses to the post-exercise CWI and HWI protocols utilised by athletes. A recent review has suggested that greater consideration of individual responses to recovery modalities will lead to improved efficacy of post-exercise recovery.\(^ {43}\) It has also been suggested that moving away from the current one-size-fits-all approach and moving towards an individualised protocol approach will maximise the performance benefits for athletes,\(^ {5,43}\) however further research is required to enable these individualised protocols to be established.

A greater understanding of the physiology surrounding CWI and HWI, the recovery needs of different performance types (e.g. endurance vs sprint) and the factors impacting them will assist in developing individualised immersion protocols likely to maximise performance benefits both in acute (minutes to days) and chronic (weeks to months) use of hydrotherapy.\(^ {5}\) This review will examine thermal and cardiovascular responses underpinning the acute and chronic performance recovery benefits of CWI and HWI, and will explore how differences in
individual characteristics and variance in protocols may influence the thermal, cardiovascular and performance responses.

2.2 Performance effects of CWI

The ultimate goal of CWI recovery is to enhance subsequent performance; however, performance benefits are not consistently demonstrated across current research. One factor likely contributing to this variance is the different exercise performance protocols utilised, in addition to the duration between exercise bouts. Performance measures utilised in the current literature vary and can be broadly categorised as whole-body endurance performance or explosive maximal performance. The differing physiological demands of these exercise modalities result in different effects on recovery, due to the associated mechanisms of fatigue, and therefore each exercise type should be considered independently. Studies by Vaile, et al. (15 min; 15 °C), Vaile, et al. (5 x 1 min; 10, 15, 20 °C and 15 min; 20 °C), Vaile, et al. (14 min; 15 °C) and Peiffer, et al. (5 min; 14 °C) found CWI better enabled the maintenance of cycling time trial (TT) performance in the heat in a subsequent bout performed between 40 and 155 min post-CWI and across subsequent days compared to active recovery or control (CON). In contrast, Peiffer, et al. and Buchheit, et al. found CWI (5 min; 14 °C and 10 °C respectively) to have no significant effect on 1 km cycling TT performance in the heat. The variability in results across these studies highlights the fact that CWI may be more effective for longer duration, endurance type exercise. Research that resulted in performance benefits utilised a cycling TT of 5-15 min duration compared a shorter duration 1 km TT (1-2 min) where negligible outcomes were observed. It has been suggested that CWI is ineffective for high intensity exercise of short durations due to 1) the lack of thermal strain from the initial bout and 2) the enhanced parasympathetic re-activation which may impact muscular contractions through the effects on oxygen consumption and glucose metabolism. However further research is required to confirm this.

Muscle function has been shown to be reduced in response to an acute exercise bout involving eccentric, high intensity or prolonged duration exercise. This has led to investigation of the impact of CWI on the recovery of muscle function using tests such as maximal voluntary isometric contractions (MVIC), jumps, and sprints. MVIC force was found to be significantly greater 24 h post-exercise with CWI (15 min; 10 °C) compared to TWI (15 min; 36 °C).
Similarly, the decrement in MVIC was reduced 24, 48 and 72 h following post-exercise CWI (2 x 15 min; 15 °C) and a faster return to baseline was observed compared to CON.\textsuperscript{26} Conversely, CWI did not assist recovery of MVIC of the knee extensors compared to a placebo TWI (15 min; 35 °C).\textsuperscript{47} Recovery of jump performance following CWI has shown more positive results indicating that CWI may be more effective for recovery of stretch-shortening cycle (SSC) exercise rather than isolated isometric or concentric movements (e.g. MVIC).\textsuperscript{45} White, et al.\textsuperscript{45} found CWI (10 min; 10 °C) reduced the decrement in drop jump height and enabled a faster return to baseline compared to CON following a running high intensity interval training session. In the same study, recovery of squat jump height following CWI was not significantly different than CON at any time point, this highlights the variance in responses across different types of performance.

Sprint performance has shown a greater tendency towards being negatively influenced by CWI. Although it has been found that CWI (5 x 1 min; 11 °C) enabled 20 m sprint performance to be better maintained,\textsuperscript{13} negligible effects have been shown as CWI (10 min; 10 °C and 2 x 5 min; 10-12 °C) was found to have no significant effect on recovery of 10-20 m sprint running performance.\textsuperscript{10,48} Sprint cycling performance has also shown mostly negative results with reductions in power following CWI observed across multiple studies.\textsuperscript{18,19,49} Sprint cycling performance was re-assessed between 5 and 35 min post-CWI in the aforementioned studies, therefore it may be possible that the short time-frame led to participants being required to perform before muscle tissue had re-warmed. With muscle temperature being an important determinant of muscular power and sprint performance,\textsuperscript{50,51} it is likely that the negative results observed are due to the muscle being cold from the CWI when the performance task was undertaken. Therefore, for CWI to be effective for recovery following sprint, power and MVC events, protocols which ensure that the primary muscles utilised for the exercise are not overcooled need to be developed. To avoid overcooling a more individualised approach which takes into account individuals body composition and body surface area may be required or a thorough warm up may need to be completed.\textsuperscript{5,50}

Previous research has also examined the effect of CWI on adaptations to both endurance and resistance training and across the research varied responses are once again reported. When examining the effect of chronic use of CWI on adaptation to endurance training, Halson, et al.\textsuperscript{52} found CWI (15 min; 15 °C) four times per week during a three-week intensified training period did not impair adaptations in endurance trained cyclists. Additionally, CWI lead to
greater improvements in 4 min TT and sprint performances compared to a CON group. Similarly, Ihsan, et al. found CWI (15 min; 10 °C) three times per week for four weeks enhanced some indices of mitochondrial biogenesis following endurance training. Conversely, the chronic use of CWI (20 min; 5 °C) three times per week for four to six weeks following endurance training was shown to interfere with regenerative processes and reduce adaptations. Chronic use of CWI has also been shown to have negative effects on training adaptation following resistance training. Indeed, Roberts, et al. found CWI (10 min; 10 °C) twice per week for 12 weeks attenuated long term gains in both muscle mass and strength. Additionally, this study found that CWI also blunted the activation of key proteins and satellite cells. Another study found chronic CWI (3x 4 min; 12 °C) twice per week for five weeks had a negative impact on training adaption following resistance training, with performance reductions of 1-5 % observed compared to CON. Similarly CWI (20 min; 10 °C) three times per week for six weeks has also been shown to reduce strength gains compared to CON.

The effect of CWI on training adaptations following a single training session has also been examined with both Ihsan, et al. and Joo, et al. finding CWI (15 min; 10 °C and 2x 5 min; 8 °C) after intermittent endurance training led to enhanced expression of peroxisome proliferator-activated receptor gamma coactivator-α (PGC1-α) which is a key regulator of mitochondrial biogenesis. Positive effects of CWI following acute training have also been found by Roberts, et al. who showed that CWI (10 min; 10 °C) following resistance training aided in the maintenance of muscle strength. Negligible effects of CWI (14 min; 15 °C) on recovery of MVIC and CMJ following a single resistance training session was observed by Argus, et al. Similarly, Peake, et al. found CWI was no more effective than active recovery at reducing inflammatory responses following resistance training. Interestingly, Schimpchen, et al. found no significant differences between the effects of CWI (10 min; 12-15 °C) and CON on weightlifting performance at a group level. However, when the inter-individual responses were examined in this study, it was evident that some athletes respond very positively with improvements in performance whereas other have negative responses with decrements in performance. Negative effects of CWI (10 min; 10 °C) following a resistance training session were observed by Figueiredo, et al. who reported a marked reduction in pre-rRNA synthesis. The effect of CWI on acute performance recovery in addition to acute and chronic training adaption is highly varied across the current literature, which highlights the need to further understand the cause of the variation both between and within studies.
2.3 Performance effects of HWI

Only a limited amount of research has examined the effect of HWI on performance with varied results. Viitasalo, et al. found HWI enabled the maintenance of neuromuscular performance variables such as isometric strength, jump height, contact time and jumping power after strength training. However, HWI has also resulted in significantly higher creatine kinase and myoglobin indicating greater muscle damage and inflammation. This is in line with findings by Vaile, et al. whereby HWI was found to be effective in maintaining isometric squat performance but ineffective in preventing swelling or reducing perceptions of pain, raising the question of whether performance changes are related to swelling and inflammation. Only one other study has examined the effect of HWI on performance, finding that HWI led to a reduction in cycling sprint and 5 min TT performance. Despite the lack of evidence to support its use HWI it is still popular among athletes and therefore requires further research to understand its impact on physiological responses and performance recovery.

2.4 Summary of performance effects

Current literature shows significant variability in the effectiveness of both CWI and HWI on performance recovery. The type of exercise performed is a critical factor contributing to the variation and it is hypothesised that endurance and SSC exercise will be more responsive to CWI and isometric exercise will be more responsive to HWI. However, there is still considerable variance in the recovery of endurance, SSC and isometric performance across current literature. Part of this variability may be related to the time-frame utilised by current research, particularly when maximal explosive performance is required shortly after CWI. Another part of this variability may be related to the individual participant and the interaction between the CWI or HWI protocol implemented and the individual body composition characteristics of the participants. Further research is required to fully understand whether a dose-response relationship exists with CWI protocols and how these responses are influenced by individual differences.
2.5 Thermal and cardiovascular responses to cold water immersion

CWI stimulates a number of thermal and cardiovascular responses that may contribute to the enhancement of performance recovery. Studies to date have focused mainly on body temperature, cardiac and haemodynamic responses to CWI at rest and following exercise. While understanding the impact of CWI on basal physiological responses provides some insight into the mechanisms by which CWI may be effective, it is perhaps most important to understand how these physiological responses might differ following exercise. This section examines the effect of CWI performed both at rest and post-exercise on body temperature, cardiovascular dynamics and blood flow.

2.5.1 Skin temperature ($T_{sk}$)

Skin is the first site to respond to cold exposure and is responsible for initiating thermoregulatory responses resulting in core temperature ($T_c$) and muscle temperature ($T_m$) change. $T_{sk}$ is significantly reduced during and following CWI without prior exercise and post-exercise CWI. Immediately following CWI without prior exercise, reductions of between 7-14 °C have been observed.66,67 Similar reductions in $T_{sk}$ of between 6-18 °C have been observed following post-exercise CWI. The extended post-CWI change in $T_{sk}$ has only been examined for 30-40 min post-CWI,31,68 and while significant reductions were found at this time point the full time-course of this “after-drop” and its impact on performance recovery remains unknown.

It is also unknown whether this variation in responses is related to the interaction between the CWI protocol utilised and the individual characteristics of the participants.

2.5.2 Muscle temperature ($T_m$)

CWI has been shown to reduce $T_m$, however the magnitude of this reduction varies significantly.20,29,67,69 There is currently limited evidence with different $T_m$ measurement and CWI methodologies making it difficult to determine the true impact of CWI on $T_m$. The variability in responses is highlighted when examining studies which have utilised the same post-exercise CWI protocol (5 min; 14 °C), but have shown vastly different results with a decrease of 2.5 °C and 0.4 °C in $T_m$ respectively.20,29 While both studies utilised the same $T_m$ measurement protocol (3 cm into the rectus femoris) and the same CWI protocol, differences existed in the time frame between the end of exercise and the start of CWI (25 min29 vs 7.5 min20) likely contributing to the differences in $T_m$ at the commencement of CWI (37.8 °C29 vs 37.0 °C20). This difference in temperature may have impacted the temperature gradient between
the water and muscle contributing in part to the variability between studies. Variability of responses is also evident following longer duration CWI protocols (10 min; 8 °C and 22 °C), with decrements of between 0.2-4.0 °C observed.\textsuperscript{67,69}

The time-course of post-CWI changes is also variable, with decrements of between 1.0 and 7.9 °C observed 15-30 min post-CWI.\textsuperscript{67,69,70} Given the relationship between \( T_m \) and muscle contractile performance,\textsuperscript{51} it is important to further examine the time-course and impact of post-exercise CWI on \( T_m \) to avoid detrimental effects and optimise beneficial performance effects. The variability in responses between studies may be due to differences in the pre-immersion state of the participants as some studies have utilised a post-exercise study design whereas others have performed CWI without prior exercise. The inclusion of exercise would likely have impacted the thermal gradient between the body and the water thus influencing thermal exchange. Another factor likely to be impacting thermal exchange is the individual body composition of the participants. It is unknown whether variation in body fat or lean mass will have the greatest impact on \( T_m \) change.

### 2.5.3 Core temperature (\( T_c \))

\( T_c \) is significantly reduced immediately post-CWI performed with or without prior exercise.\textsuperscript{71} The extent and time-course of this reduction is varied, and with inconsistencies in study methodologies it is difficult to determine exactly how CWI impacts \( T_c \) and subsequent performance. When comparing studies matched for protocol, variability in the immediate post-CWI (5 min; 14 °C) responses become obvious with changes of -0.4 °C,\textsuperscript{9} +0.4 °C,\textsuperscript{20} and -0.3 °C\textsuperscript{29} observed. It may be postulated that the small changes in \( T_c \) observed during short duration CWI may be related to the initial re-distribution of warm blood from the periphery to the core which enables the preservation of \( T_c \). Furthermore, it is likely that such a short exposure to the CWI stimulus does not sufficiently impact tissue temperature and blood flow thus the potential beneficial effects of a 5 min CWI may be minimal.

However, the varied \( T_c \) response has also been shown to persist for up to 90 min\textsuperscript{71} post-CWI with decrements ranging from 0.1-2.3 °C 30 min post-immersion regardless of the duration of CWI (5-20 min). \( T_c \) has not been examined beyond 90 min post-CWI and therefore the full time-course of the change and recovery remains unknown. As with \( T_{sk} \), \( T_c \) at the commencement of subsequent performance can potentially have a “pre-cooling” effect and enhance the athlete’s heat storage capacity, therefore enabling more work to be performed.
before reaching a critical \(T_c\). Future studies should focus on determining the exact degree of change in \(T_c\) that leads to an optimal “pre-cooling” effect for subsequent performance and how to induce this change across individual athletes/participants.

### 2.5.4 Cardiovascular dynamics

Increases in hydrostatic pressure with water immersion cause venous and lymphatic compression. Venous return is sensitive to external pressure and when hydrostatic pressure exceeds venous pressure, blood flow is redirected from peripheral to central areas. This redistribution of blood flow leads to an increased central blood volume (CBV) of \(1.9 \pm 0.5\) L, which has been shown to increase right atrial pressure and pulmonary arterial pressure. Therefore stimulating an increase in cardiac contractility resulting in an increased stroke volume (SV) of up to 5.9\% or 110 ± 2.4 ml. Similar increases in cardiac output (Q) of 4.4\% to 30\% have been observed during TWI.

Research examining the effect of CWI on cardiac dynamics is limited, therefore assumptions are guided by research examining cold exposure. Cold temperatures can activate shivering thermogenesis, which increases venous return via the activation of muscle pump activity, although this does not always occur. Cold exposure also increases sympathetic activity, and the resultant peripheral vasoconstriction facilitates redistribution of blood increasing CBV. These vascular changes contribute to increases in SV, Q, total peripheral resistance and blood pressure. Indeed, a significant increase in Q and SV following CWI (15 min; 15 °C) performed at rest has been reported. While these specific cardiac responses have not been fully assessed in response to post-exercise CWI, it is likely any such improvements in cardiac output would enhance oxygen delivery and the recovery of aerobic performance. However, future research is required to fully elucidate the cardiovascular changes induced by post-exercise CWI.

### 2.5.5 Limb, skin and muscle blood flow

Consistent with the notion that cold exposure induces peripheral vasoconstriction, most studies have observed reductions in limb blood flow during and following CWI. Femoral artery vascular conductance is reduced by 75 % following post-exercise CWI, and 30 % following CWI without prior exercise. Therefore, the reduction in vascular conductance, which is reflective of vessel diameter, may indicate the occurrence of vasoconstriction following CWI performed post-exercise and at rest. Leg blood flow responses following CWI without prior exercise have found CWI (20 min; 13 °C) to have no acute effect on leg blood flow. In contrast,
Vaile, et al.\textsuperscript{5} found significant reductions in blood flow to the arm and leg from 5-40 min following post-exercise CWI (15 min; 15 °C). Large increases in the leg-to-arm blood flow ratio were also reported, which were taken to reflect a greater reduction in skin flow than muscle flow, and these changes were correlated with the magnitude of the fall in $T_c$ with CWI.

To understand the significance of these blood flow changes it is important to assess blood flow to the skin and muscle. The effect of CWI (10 min; 8 and 22 °C) on skin blood flow has been examined in normothermic conditions by two previous studies. It was found that regardless of the pre-immersion state (rested or post-exercise), a significant reduction in cutaneous vascular conductance of the thigh occurs. This significant reduction was shown to persist from 1-30 min post-CWI.\textsuperscript{67,69} Skin blood flow responses to post-exercise CWI (5 min; 9 and 15 °C) in hot conditions have also been examined and cutaneous vascular conductance was found to be reduced by 50 % compared to pre-immersion values.\textsuperscript{78}

There have been no direct assessments of muscle blood flow in response to CWI as current technology in this area is lacking. The closest measure to muscle blood flow comes from near infrared spectroscopy (NIRS) which measures the tissue oxygenation through the oxygenated and deoxygenated haemoglobin content.\textsuperscript{79} Muscle tissue oxygenation, measured by NIRS, is dependent on metabolic activity and blood perfusion, and was found to be attenuated following post-exercise CWI (15 min; 10 °C) in normothermic conditions and muscle blood volume significantly reduced following post-exercise CWI (5 min; 9 and 15 °C) in the heat. This lends some support to the notion that CWI reduces intramuscular metabolism, although the direct effect on muscle perfusion cannot be determined. Reductions in $T_m$ might be expected to reduce blood flow (perfusion), muscle metabolism, inflammation and oedema. Conversely, vasoconstriction of the skin, as evidenced by a reduction in skin blood flow with CWI, might enhance the distribution of blood towards working muscles during subsequent performance. Further studies including direct investigations of limb, skin and muscle blood flow in response to CWI are required to better understand the influence of blood flow changes on performance recovery.
2.6 Thermal and cardiovascular responses to hot water immersion

2.6.1 Skin, muscle and core body temperatures

Thermal homeostasis during exposure to the heat is initiated by signals from thermoreceptors located in the skin and core. Much like the thermoregulatory responses to cold exposure, heat exposure stimulates peripheral thermoreceptors which then provide afferent input to the hypothalamus which subsequently signals the body to initiate responses to regain thermal homeostasis. When $T_c$ rises above its “set point” the sympathetic nervous system dilates the cutaneous vascular beds which increase cutaneous blood flow. This vasodilatation leads to blood flow being redirected to the skin resulting in an increased $T_{sk}$. The increased $T_{sk}$ occurs as a result of convective heat transfer from the blood to the skin to bring the two temperatures nearer. The previously mentioned “set point” varies among individuals and ranges between 36.5-37.5 °C. Another physiological mechanism by which the body regulates temperature is thermoregulatory sweating, which normally commences when $T_c$ reaches 37 °C and closely parallels increases in body temperature. Sweating is a means of evaporative cooling as sweat on the skin's surface is changed from water to vapour, causing the body to lose 0.58 kcal of heat for every 1 g of water evaporation. However, in humid environments or during water immersion sweat is unable to evaporated effectively and consequently core body temperature rises.

Exposure to heat stimulates cutaneous thermoreceptors which leads to vasodilatation and a redirection of blood flow to the skin. Minimal research has examined the effect of HWI on various body temperatures. HWI (15 min; 43.8 °C) was found to lead to a significant increase in both $T_{sk}$ and $T_c$ immediately post-immersion compared to CON. Similarly Vaile, et al. found HWI (15 min; 38 °C) led to a significant increase in $T_c$ immediately post-immersion. $T_m$ has also been found to increase immediately post-HWI, with an increase of 2.83 °C immediately after 20 min of leg only immersion at 40 °C being observed. Additionally, Gregson, et al. found that HWI at 44 °C to the level of the gluteal fold resulted in participants reaching the target $T_c$ of 38 °C after an average of 29 ± 5.3 min.

2.6.2 Cardiovascular dynamics

HWI is believed to impact cardiovascular physiology as a result of its influence on cutaneous vasodilatation which has a direct impact on heart rate (HR) causing it to increase, leading to an increased $Q$. examined the effect of 15 min of whole body HWI at 37 °C and 39 °C on a number
of cardiovascular measures and found HR increased by 10 % in 37 °C water and by 35 % in 39 °C water. SV was found to increase by approximately 70 % in both water temperatures. This increase in HR and SV led to an increased Q. Q was shown to increase by 80 % in 37 °C and by 120 % in 39 °C water. also found significant increases in both HR and Q during 15 min of whole body immersion in 43.8 °C. This research has only examined the effect of HWI performed at rest on cardiovascular dynamics and further research is required to examine the effect of post-exercise HWI when the participants HR, SV and Q are already elevated due to the effects of exercise.

2.6.3 Limb, skin and muscle blood flow

Only two studies have examined the effect of HWI on blood flow; Bonde-Petersen, et al. measured cutaneous, subcutaneous and muscle blood flow in the forearm after 15 min of whole body immersion in 43.8 °C. Cutaneous and muscle blood flow were found to increase compared to CON by 24 % and 8 % respectively. In contrast sub-cutaneous blood flow was found to decrease by 43 %. Fiscus, et al. examined the effect of HWI, 20 min at 40 °C immersed to the knee on whole limb blood flow to the leg and found a significant increase compared to CON.

2.6.4 Summary of thermal and cardiovascular responses to CWI and HWI

Both resting and post-exercise CWI and HWI results in significant thermal and cardiovascular changes. The magnitude and time-course of these changes are varied therefore determining the true physiological effect of both CWI and HWI is difficult. Much of this variability is likely related to the pre-immersion state of the athlete, disparity in immersion protocols, and individual body composition differences. These variable thermal and cardiovascular responses to CWI and HWI are likely the cause of the variation in performance recovery.

2.7 Water immersion protocols

A contributing factor to the physiological and performance variation is the dose of cooling provided by CWI or heating provided by HWI. No “gold standard” currently exists for CWI and HWI and protocols tend to be based on those used practically without strong efficacy or physiological evidence.
2.7.1 Water temperature

Water is an effective conductor causing heat exchange to occur 25 times faster than air, placing significant thermal stress on the body. Water temperature has an impact on the duration and level of immersion utilised, with CWI colder temperatures inducing a greater initial “cold shock”, increasing discomfort and, possibly limiting exposure time. Likewise, with HWI, warmer temperatures place the body under greater heat stress and may increase discomfort. The impact of water temperature during CWI was examined by comparing immersion in 8 and 22 °C, and unsurprisingly 8 °C resulted in a larger decrement in $T_c$. Water temperatures of between 10 and 15 °C appear to be optimal for performance recovery. There is very minimal research on HWI therefore it is not possible to determine optimal temperatures for performance recovery. A greater understanding of the impact of water temperature on body temperature change and performance recovery is required to enable the optimisation of protocols, therefore future research should look to examine this.

2.7.2 Immersion duration

Duration of immersion is likely to impact the cooling induced by CWI or heating induced by HWI, with a longer exposure to the temperature stimulus resulting in a greater thermal effect. CWI durations of 10-20 min have been suggested as optimal for performance recovery, as anything shorter may not cause sufficient tissue temperature change. However, duration needs to be explored in conjunction with water temperature, as colder or hotter temperatures will have a greater thermal stress and therefore cause tissue temperature to change at a faster rate. The impact of immersion duration is evident after examining responses when participants completed CWI to the mid-sternum at 14 °C for 5, 10 and 20 min. Pre-immersion $T_m$ was 38.8 °C for all trials and immediate post-immersion decrements of 2.5 °C (5 min), 4.0 °C (10 min) and 6.0 °C (20 min) were observed. $T_c$ responded in a similar manner, with a pre-immersion $T_c$ of 38.8 °C for all trials and immediate post-immersion decrements of 0.3 °C (5 min), 0.6 °C (10 min) and 1.0 °C (20 min) observed. This duration effect continued into the post-recovery period with $T_c$ at 30 min post-immersion showing reductions of 1.3 °C (5 min), 1.5 °C (10 min) and 2.3 °C (20 min). The interaction immersion duration and water temperature is complex and further research is required in order to enable protocol prescription to be optimised.
2.7.3 Depth of immersion

The level of immersion affects thermal and physiological responses in two ways; firstly if more of the body is exposed there will be greater surface area for heat exchange to occur; secondly, the deeper the immersion, the greater the impact of hydrostatic pressure.\(^{40}\) The influence of immersion depth becomes evident when comparing studies that utilised similar CWI protocols (15 min; 15 °C), differing only in immersion depth.\(^{5,49}\) Immediately post-CWI Vaile, et al. \(^5\) (whole body immersion) observed a decrement in T_c of 1.3 °C whereas Crampton, et al. \(^{49}\) (leg immersion) only observed a decrement of 0.4 °C; therefore less surface area exposed to the cold stimulus may result in smaller T_c changes. A comparison of two studies with different CWI protocols (5 min, 14 °C, whole body immersion\(^{20}\) and; 5 min, 10 °C, legs only), found CWI to induce the same immediate post-immersion T_c change (0.4 °C), showing that different protocol combinations can have the same impact. So, while one study had a greater surface area exposed to the cold stimulus, the other utilised a lower water temperature leading both studies to result in the same degree of T_c change. Therefore, it is important for future research to examine the interaction between these protocol factors.

2.7.4 Mode of immersion

The mode of immersion is another protocol factor which varies across current research, with studies either utilising one continuous immersion ranging from 5-20 min or intermittent immersion which involves multiple short immersions of 1-5 min separated by passive rest outside of the water for durations of 1-2.5 min.\(^{38}\) Only one study has compared continuous and intermittent immersion and reported that both protocols were equally effective in the recovery of performance and perceptual measures.\(^{92}\) To date no research has compared the effect of continuous and intermittent immersion on physiological responses, however it may be postulated that the frequent change in thermal gradient occurring each time the participant moved between the cold water and the warmer air would lead to a greater reduction in body temperature. Nevertheless, further research is required to fully understand the impact that immersion mode has on physiological and performance responses to water immersion.

2.7.5 Summary of water immersion protocols

Water temperature, plus the duration, depth and mode of immersion all significantly impact the magnitude and rate of thermal change in response to CWI and HWI. The interaction between each of these factors is complex and while it has been shown that different
combinations of these three factors can result in the same degree of $T_c$ change, it is unknown whether duration, temperature or depth will have the greatest impact upon thermal and cardiovascular responses. It is also unknown what the optimal combination of these factors is and further research is required to fully understand the impact of temperature, duration, depth and mode of immersion and how they may interact with individual differences in physique.

2.8 Individual characteristics and responses to water immersion

Whilst some of the variability in physiological and performance responses to CWI and HWI can be explained by methodological differences or variation in water immersion protocols, there remains some variability within the literature, which indicates that individual characteristics may influence responses to water immersion. Given the known impact of physique traits on thermoregulatory responses to cold and hot exposure, it is important to consider these traits when attempting to interpret the variance in the effectiveness of CWI and HWI.

2.8.1 Physique traits

2.8.1.1 Body mass, body surface area and surface area to mass ratio

Body surface area (BSA), body mass (BM) and body surface area to mass ratio (BSA:M) are considered to be important factors impacting one’s ability to maintain thermal homeostasis. BSA influences individual responses to thermal exposure as heat exchange via evaporation, convection and conduction all depend on the available surface area. While BM affects the rate of heat production and heat storage, a larger BSA should theoretically cause heat exchange to be increased. However, while overweight individuals have a greater BSA than lean individuals, their rates of heat loss is comparatively lower due to a greater BM. The BSA:M ratio has been proposed to reflect this interaction between body trait characteristics, where a larger BSA:M facilitates heat loss and a smaller BSA:M facilitates body insulation (heat storage). From thermoregulatory studies we know that the increase in metabolic rate and decrease in $T_c$ during exposure to cold air is significantly greater in those with a higher BSA:M than in those with a lower BSA:M. However, no studies to date have examined the impact of BSA:M on responses to CWI or HWI.
2.8.1.2 Body fat

Body fat is considered one of the most important body composition factors impacting the effectiveness of CWI as it influences both heat conductivity and blood flow. Body fat has a low heat conductivity providing greater insulation and thermal resistance compared to skin and muscle. This insulating effect is thought to affect the magnitude and rate of \( T_m \) change as well as the rate of re-warming following cold exposure. Gastrocnemius \( T_m \) was found to decrease at a slower rate during cooling in participants with high, compared with low, subcutaneous fat, and returned towards baseline at a slower rate. Additionally, significant differences in the decrease in maximum \( T_m \) were observed between groups where the decrement was greatest in those with less body fat. It is interesting to note, however, that the standard deviations of the drop in 1 cm \( T_m \) ranged between 4.4-4.6 °C. This variance indicates the wide range of individual responses and highlights the fact that there may have been individuals who responded more favourably than others in each of the body composition groups.

Blood flow is also impacted by body fat as individuals with high body fat have been shown to have a lower than average blood volume per unit weight. This reduced blood volume influences conductive heat transfer through the tissues improving the insulative capacity of individuals with greater body fat. Body fat not only varies from sport to sport but even within sports significant differences in body fat exists. This highlights the fact that even in the same team, athlete’s body compositions may vary substantially, therefore individualising CWI and HWI protocols may be warranted.

2.8.1.3 Muscle mass

Muscle tissue has a significant impact on individual thermoregulatory responses. Indeed, vasoconstricted muscle was found to provide approximately 80 % of total body insulation during resting water immersion. The depth of measurement affects \( T_m \) change, whereby deeper muscle tissue (e.g. 3 cm depth) takes longer to cool and re-warm than superficial muscle sites (e.g. 1 cm). This was supported by the finding that \( T_m \) at 1 cm decreased by 6 °C, whereas \( T_m \) at 3 cm only decreased by 1.5 °C immediately following post-exercise CWI. Muscularity has been shown to impact \( T_c \) responses to exercise, particularly in hot environments, with mesomorphic participants having higher \( T_c \) and greater risk of hyperthermia than athletes with lower muscle mass. Mesomorphic athletes are likely to present with higher \( T_c \) post-exercise and one might conclude that a greater dose of CWI would be necessary to account for the higher
temperatures in these individuals. In contrast, it may also be concluded that the higher $T_c$ may create a greater temperature gradient between the body and the water therefore increasing the cooling rate, which is in line with Newtons law of cooling.\(^9\) While it is well established that muscle mass impacts upon thermal responses to both exercise and CWI, it has not yet been determined whether a greater dose of CWI is required to enhance recovery for mesomorphic athletes/participants or whether the dose of HWI needs to be altered for mesomorphic athletes/participants.

### 2.8.2 Other individual factors

Other individual differences such as age, gender and ethnicity also have the potential to impact the responses to CWI and HWI, and this is largely due to their relationship with body composition.

#### 2.8.2.1 Gender

Thermoregulatory responses vary greatly between males and females, which can be attributed mainly to the differences in body size and composition between males and females.\(^3\) Females tend to have a greater total body fat and thicker layers of subcutaneous fat as well as greater surface area to mass ratios compared to males.\(^1\) While greater amounts of subcutaneous fat is associated with greater insulation and lower shivering thermogenesis in response to cold conditions,\(^1\) it seems that the surface area to mass ratio may play a greater role in the maintenance of body heat during cold exposure. McArdle et al.\(^1\) found the extra body fat in female participants provided no benefits to thermoregulation. When males and females of the same body fat were compared, females were found to cool to a greater extent. This confirms the assumption that the lower surface area to mass ratios possessed by males is more favourable for heat retention.\(^1\)

The primary differences between males and female in terms of thermoregulation in the heat exist around sweating mechanisms. Females have more heat-activated sweat glands per unit of skin, and also begin sweating at higher $T_{sk}$ and $T_c$ compared to males.\(^1\) Sweat rates also differ greatly between genders as males have been reported to have higher sweat rates than females in hot-dry and hot-wet climate conditions.\(^1\) Despite these differences women still show equal heat tolerance to men regardless of a lower sweat output.\(^1\)
Another factor influencing the different gender responses to thermoregulation is the menstrual cycle, during the luteal phase, $T_c^{104}$ and $T_{sk}^{34}$ are higher than during the follicular phase. Thermosensitivity is also affected by the menstrual cycle as changes in estrogen result in heightened thermosensitivity.$^{34}$ The changing female hormone patterns during the menstrual cycle also have numerous effects on the cardiovascular system and blood flow$^{105}$ which have the potential to impact upon the effectiveness of thermoregulatory vasodilatation and vasoconstriction which are two of the primary responses controlling thermal homeostasis during both hot or cold exposure.

2.8.2.2 Age

Thermoregulation in young children and the elderly is significantly different to that of adults, primarily due to lower subcutaneous fat$^{34}$ and a large body surface area to muscle mass$^{81}$ compared to adults. These body composition differences make it more difficult for both the young and the elderly to maintain thermal homeostasis and places them at greater risk of cold injury.$^{34}$ The elderly also experience reduced responsiveness of cutaneous blood flow to cold exposure and erratic temperature regulation$^{34}$ which diminish their ability to cope with hot and cold conditions. In addition to this many elderly people also take prescription medication which may influence thermoreceptors and effector function.$^{34}$

2.8.2.3 Ethnicity

Ethnicity or race is another factor that is believed to impact upon an individual’s thermoregulatory responses. It is believed that a combination of genetic variation/genotype adaptations and adaptations to environmental stresses/phenotype adaptations$^{106}$ explain the disparity in physiological responses to cold exposure observed between humans with different ethnic backgrounds. Research has examined the difference in $T_c$, $T_{sk}$ and metabolic rate responses to cold exposure between Caucasian males and African American$^{107}$, Bantu$^{108}$ and Australian Aboriginal$^{109}$ males.

Genetic differences in the initiation of shivering thermogenesis at cold ambient temperatures have been observed between Aborigines and Caucasians.$^{106}$ Another observed genetic difference between ethnic groups is the distribution of cutaneous arteriovenous anastomoses. Rennie and Adams$^{107}$ identified this difference between Caucasian and African American males and attributed the differences in cold induced vasodilation observed between these groups to be a result of this genetic difference. Phenotypic differences between ethnic groups
typically involved differences in morphology\textsuperscript{106} and anthropometric characteristics.\textsuperscript{108} Factors such as subcutaneous adipose tissue thickness, height, weight and body surface area are believed to explain why ethnic groups such as African American have greater heat conductance than Caucasians.\textsuperscript{107,108} Wyndham, et al. \textsuperscript{108} concluded that body composition variability between ethnic groups explains the major differences observed in heat conductivity of peripheral tissues between these groups.

\subsection*{2.8.3 Summary of individual characteristics and responses to water immersion}

Given the potential impact of these individual factors on responses to CWI and HWI, practitioners should give consideration to the body composition, age, gender and ethnicity of the athlete. Water immersion protocols utilised for different teams (e.g. males v females) or different individuals within a team (e.g. forwards vs backs in rugby), may need to differ in order to provide optimal benefits for each group of athletes. However, further research is required to determine optimal protocols for each group of athletes.

\section*{2.9 Conclusion}

This review demonstrates that a number of factors have the potential to impact an individual’s response to CWI and HWI, and failure to recognise these in the individual prescription of water immersion may impact the effectiveness of recovery. This review has focused on temperature and cardiovascular responses to CWI and HWI as these are likely to underpin performance changes, and are likely to also influence other outcomes including markers of inflammation, muscle damage and performance. Future research must further investigate the physiological responses to CWI and HWI to gain an understanding of the optimal degree of change so that appropriate protocols may be determined. It is also important to further examine all factors which contribute to the variance. Physique traits such as body fat, muscle mass, and their regional distribution, plus body surface area to mass ratios may influence thermal and physiological responses to water immersion. These individual characteristics have been shown to impact thermal responses to temperature extremes,\textsuperscript{110} however the impact on responses specifically to the CWI and HWI protocols utilised for athletic recovery remains unknown.\textsuperscript{5,110}
Chapter Three – General Methods

This section outlines and provides additional detail for the general methods used throughout this PhD research and includes reference to which chapters they were utilised in.

3.1 Physiological measures

3.1.1 Core temperature ($T_c$)

$T_c$ was measured using a disposable rectal thermometer (Monatherm, Mallinckrodt, USA) self-inserted 10 (Study two, Chapter Five) to 12 cm (Study Three, Chapter Six) beyond the anal sphincter and was logged continuously at 10 s intervals throughout each trial (Squirrel 2040-2F16, Grant Instruments, England). It was our intention to use the same depth of measurement (10 cm) for both studies however after pilot testing for Study Three, there were some concerns with the probe remaining in position during data collection therefore the depth was increased to 12 cm.

Prior to testing, each rectal thermometer was individually calibrated against a reference thermometer PT100 (D209, RS, Sydney, Australia) connected to a digital multimeter (34410A, Agilent, USA) that logged data every 10 s. The rectal thermometers were immersed in batches of eight with the reference thermometer in a stirred water bath at 35 and 38 °C, for 15 min. The first 5 min were used as a settling period, then from the final 10 min the average difference between the individual rectal thermometer and the reference thermometer was calculated and applied as a correction factor. This calibration process was based upon the recommendations of Versey, et al. 111

3.1.2 Skin temperature ($T_{sk}$)

$T_{sk}$ was measured in Studies Two and Three (Chapters Five and Six) using iButton (DS1922L, Maxim Integrated Products Inc., USA) temperature sensors taped (Leuko Rigid Sports Tape, Beiersdorf Australia Ltd, AUS) to the skin at four sites: chest, anterior mid-forearm, anterior lower-thigh and posterior mid-calf on the left side of the body. 68 Temperature was logged every
10 s at each of the four sites. Mean $T_{sk}$ was calculated using the following equation $T_{sk} = 0.3 \times (T_{chest} + T_{arm}) + 0.2 \times (T_{thigh} + T_{leg})$.112

3.1.3 Muscle temperature ($T_m$)

$T_m$ was measured in Study Two (Chapter Five) at the mid-point of the inguinal fold and anterior patella113 in the muscle belly of the vastus lateralis. A 2 mm diameter flexible Teflon multi-sensor temperature probe (T-336, Physitemp Instruments, USA) was inserted 3 cm below the subcutaneous fat. Each probe consisted of three thermocouples positioned at 1, 2, and 3 cm depths. Upon arrival to the laboratory the site was scanned using B-mode ultrasound (Terason t3000 Ultrasound System, Teratech Corporation, USA) to measure subcutaneous fat depth to ensure all three thermocouples would be inserted into muscle tissue. This site was then marked with a surgical marker (Secureline, Aspen Surgical, USA) and dermal anaesthetic cream (5 mg Emla, AstraZeneca Pty Ltd, AUS) applied for a minimum of 30 min and removed immediately prior to the insertion of the probe. The probe site was covered with water proof dressings (Tegaderm, 3M, USA) for the remainder of the trial (Figure 3.1). Each research assistant who inserted the intramuscular temperature probes underwent appropriate training overseen by Australian Institute of Sport medical officers. $T_m$ was wirelessly transmitted (Thermes USB Data Acquisition System, Physitemp Instruments, USA) and data from each of the three depths logged every 10 s (DASY Lab 10.0.1, Measurement Computing, USA). A mean of all three depths was calculated for each post-exercise time point.

![Figure 3.1: Intramuscular temperature probe insertion.](image-url)
Before use, each probe was cleaned and sterilised according to manufacturer’s recommendations. The cleaning process commenced with the probe being soaked for 10 min in a medical grade enzymatic cleaner (3M rapid multi-enzyme cleaner, 3M, Taiwan). This was then followed by 15 min in an ultrasonic cleaner (GT SONIC-P2, GT Ultrasonic Co, China) at 50 kHz in a medical grade enzymatic cleaner (3M rapid multi-enzyme cleaner, 3M, Taiwan). Thereafter each probe was rinsed under hot running water for 1-2 min to remove all cleaning solution. Each probe was then visually inspected for cleanliness and/or damage before being dried with a lint free cloth and placed in a sterilising pouch (self-sealing sterile pouches, Perfection, China). The sterilising pouches were placed into a steam autoclave (2340EKA, Tuttnauer, Netherlands) in batches of six to eight along with an indicator strip (Comply SteriGauge, 3M, USA). The probes underwent a steam autoclave cycle for 7 min at 134 °C. Once the cycle was complete the probes remained in the autoclave until cooled. After cooling each sterilising pouch was visually inspected to ensure the packaging was intact and the chemical indicators had changed colour to indicate a successful sterilisation.

Prior to testing and sterilisation each T-336 probe was individually calibrated against a reference thermometer PT100 (D209, RS, Sydney, NSW, Australia) which was connected to a digital multimeter (34410A, Agilent, Santa Clara, CA, USA) which logged data every 10 s. Each T-336 probe and the reference thermometer were immersed in a stirred water bath at 35 and 38 °C. Probes were immersed for 15 min with the first 5 min used as a settling period, and then from the final 10 min the average difference between the individual probe and the reference thermometer was calculated and applied as a correction factor. This calibration process was based upon the recommendations of Versey, et al. 111

3.1.4 Forearm and calf blood flow (venous occlusion plethysmography)

Limb blood flow for both the arm and leg was measured in Study Two (Chapter Five) via venous occlusion plethysmography. Participants lay supine with the right arm and both legs raised on foam blocks slightly above the level of the heart. Mercury-in-rubber strain gauges (Hokanson, USA) were placed around the maximal girth of the right calf and on the forearm 5 cm distal to the olecranon process (Figure 3.2). The position of the strain gauges and ECG electrodes was marked with a surgical marker (Secureline, Aspen Surgical, USA) prior to baseline measurements to ensure they were positioned in the same place for each measurement. Plethysmograph and single lead electrocardiograph signals were continually captured at 1 KHz and stored digitally (Powerlab, ADInstruments, NSW, Australia). Blood flow was assessed by
inflating the limb pressure cuff to a venous occluding pressure of 60 mmHg for a 10 s period, and measuring the rate of rise in limb volume (strain gauge signal) over the period of two cardiac cycles. The strain gauge was calibrated in situ on the limb according to manufacturer's guidelines to give a 0.1 V change in voltage equal to a known change (%) in limb volume. This calibration then provided a correction factor to be later used in the calculation of blood flow.

On each occasion, blood flow was measured in triplicate at the leg and then in the arm, with 10 s separating each measurement. Triplicate measures were then averaged to provide a single measure of leg blood flow and arm blood flow at each time point. Foot and hand circulation was excluded from the measures by inflating ankle or wrist cuffs, respectively, to 220 mmHg. Blood flow was expressed as millilitres per volume of tissue per minute (i.e. mL.100mL\(^{-1}\).min\(^{-1}\)). For each measurement, blood flow was calculated over the period of the first cardiac cycle free of cuff inflation artefact using the following equation:

\[
\text{Blood Flow (mL.100mL}^{-1}\text{.min}^{-1}) = \frac{(\text{change in limb volume / correction factor}) \times 60}{\text{change in time}}
\]

Where the change in limb volume was assessed as the change in voltage output of the strain gauge over one cardiac cycle; the correction factor was the known change in limb volume provided during calibration of the strain gauge; and the change in time was the duration of one cardiac cycle for the measurement.
3.1.5 Blood pressure

Brachial blood pressure (BP) was measured in Study Two (Chapter Five) between arm and leg blood flow measures (Omron BP791IT, Omron Healthcare, USA). The blood pressure cuff was placed on the left bicep and the participant was instructed to lay still and quiet during the measurement.

3.1.6 Heart rate

Heart rate (HR) was measured in Studies Two and Three (Chapters Five and Six) using a Polar heart rate monitor (S810i, Polar, Finland). Participants wore a plastic transmitter chest strap at the level of the xiphoid process and a watch receiver on their left wrist. HR data was logged to the watch every five seconds throughout the trials. Post-testing data was downloaded in Polar precision performance software (Polar, Finland) and exported to Microsoft Excel. 30 s averages were recorded for each time point.
3.2 Perceptual Measures

3.2.1 Thermal sensation

Perceived thermal sensation was measured in Studies Two and Three (Chapters Five and Six) on a scale of zero (unbearably cold) to eight (unbearably hot). Figure 3.3 shows the scale used. Participants were familiarised with this scale during the familiarisation visits for both studies.

![Thermal Sensation Scale (TSS)]

<table>
<thead>
<tr>
<th>Scale (TSS)</th>
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<tbody>
<tr>
<td>0.0</td>
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<td>0.5</td>
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<td>1.5</td>
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<td>7.5</td>
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<td>8.0</td>
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</tbody>
</table>

Unbearably cold
Very cold
Cold
Cool
Comfortable
Warm
Hot
Very hot
Unbearably hot

Figure 3.3: Thermal Sensation Scale.
### 3.2.2 Rating of perceived exertion (RPE)

Perceived exertion was measured in Studies Two and Three (Chapters Five and Six) on a scale from 6 (no exertion at all) to 20 (maximal exertion) (Figure 3.4). Participants were familiarised with this scale during the familiarisation visits for both studies.

<table>
<thead>
<tr>
<th>Rating of Perceived Exertion (RPE)</th>
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<tbody>
<tr>
<td>6</td>
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<td>20</td>
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</tbody>
</table>

Figure 3.4: Rating of perceived exertion scale.
3.2.3 Perceived fatigue

Perceived fatigue was measured in Study Three (Chapter Six) on a 10-point scale (0 = nothing at all, 10 = extremely high) (Figure 3.5).\textsuperscript{115} Participants were familiarised with this scale during the familiarisation visits for study three.

<table>
<thead>
<tr>
<th>Whole Body Fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
</tr>
<tr>
<td>Nothing at all</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>Extremely low</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>Very low</td>
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<tr>
<td>High</td>
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<tr>
<td>6.0</td>
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<tr>
<td>7.0</td>
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<tr>
<td>Very high</td>
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<tr>
<td>8.0</td>
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<tr>
<td>9.0</td>
</tr>
<tr>
<td>10.0</td>
</tr>
<tr>
<td>Extremely high</td>
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</tbody>
</table>

Figure 3.5: Whole body fatigue scale.
3.2.4 Perceived muscle soreness

Perceived soreness was measured in Study Three (Chapter Six) on a 10-point scale (0 = nothing at all, 10 = extremely high) (Figure 3.6). Immediately prior to rating muscle soreness, participants were required to perform a standardised half squat to ensure they experienced the same movement/sensation on each occasion.\(^{115}\) Participants were familiarised with this scale during the familiarisation visits for study three.

<table>
<thead>
<tr>
<th>Whole Body Soreness</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>Nothing at all</td>
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<tr>
<td>0.3</td>
<td></td>
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<tr>
<td>0.5</td>
<td>Extremely low</td>
</tr>
<tr>
<td>1.0</td>
<td>Very low</td>
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<tr>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>Low</td>
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<td>Moderate</td>
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<tr>
<td>5.0</td>
<td>High</td>
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<tr>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>7.0</td>
<td>Very high</td>
</tr>
<tr>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>Extremely high</td>
</tr>
</tbody>
</table>

Figure 3.6: Whole body soreness scale.
3.2.5 *Total quality of recovery (TQR)*

Perceived recovery was measured in Study Three (Chapter Six) on a scale from 6 (no recovery) to 20 (maximal recovery) (Figure 3.7). Participants were familiarised with this scale during the familiarisation visits for study three.

<table>
<thead>
<tr>
<th>Total Quality Recovery (TQR)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>No recovery at all</td>
</tr>
<tr>
<td>7</td>
<td>Extremely poor recovery</td>
</tr>
<tr>
<td>8</td>
<td>Very poor recovery</td>
</tr>
<tr>
<td>9</td>
<td>Poor recovery</td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Reasonable recovery</td>
</tr>
<tr>
<td>12</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Good recovery</td>
</tr>
<tr>
<td>14</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Very good recovery</td>
</tr>
<tr>
<td>16</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Extremely good recovery</td>
</tr>
<tr>
<td>18</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Maximal recovery</td>
</tr>
<tr>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.7: Total Quality Recovery scale.
3.3 Performance Measures

3.3.1 Maximal oxygen uptake test (VO_{2\text{max}})

A maximal oxygen uptake test was conducted in Studies Two and Three (Chapters Five and Six) during pre-trial testing, to determine the power output required in Chapter Five and to determine capability to complete the HIIT protocol in Chapter Six. Participants completed a maximal test on a cycle ergometer (Excalibur Sport, Lode, Netherlands). The tests commenced at 125 W and increased by 25 W every 3 min and participants continued until volitional exhaustion. Oxygen consumption was measured utilising an automated Douglas bag system. Expired gas was collected in 120 L aluminised Mylar bags for a period of 30 s. When one bag was being filled, another was being analysed and then evacuated. At the end of 30 s the bags were swapped and the cycle was repeated. This system used Amatek analysers for oxygen (Model: S-3A/I) and carbon dioxide (Model:CD-3A) analysis. Prior to testing the analysers were calibrated using an automated calibration cycle using three gravimetrically prepared gas mixtures (NATA certified). Successful calibration required that all gases were measured to within 0.02 % of their stated values. Gas samples were dried using a combination of Nafion tubing and a desiccant. Bag volume was determined using an instrumented syringe to evacuate the bag. The syringe displacement was measured (Tempsonics Magnetostrictive Linear-Position Sensors) along with gas temperature and pressure (Druck PMP1400 pressure transducer) to determine the gas volume which was then normalised back to standard temperature and pressure for all subsequent calculations. The system used the traditional Haldane method for calculating inspired gas volumes. Blood lactate (Lactate pro 2, Akray, Japan), heart rate (Polar RS800cx, Polar electro oy, Finland) and RPE were recorded at the end of each 3 min stage.

3.3.2 Time trial performance (TT)

The 4 min maximal cycling TT was performed (Chapter Six) on an air-braked cycle ergometer (Wattbike Ltd, Nottingham, UK). Participants were instructed to complete as much work (distance) as possible throughout the 4 min period and were blinded to all feedback except time. Total work (kJ), total distance (m) and average power (W) performed in each TT were recorded. Reliability of the TT was assessed by examining the baseline performance across the two experimental trials for each participant, total work was found to have a CV of 2.3 %, total distance had a CV of 0.9 % and average power had a CV of 2.3 %.
3.3.3 Countermovement jump (CMJ)

Participants performed a body weight (CMJ-BW) and a weighted (CMJ-WT) CMJ test in Study Three (Chapter Six), consisting of two sets of three maximal CMJ with the average of the six jumps at each time point used for analysis. CMJ-BW was performed with a lightweight aluminium bar (0.4 kg), while the CMJ-WT was performed with a load equivalent to 40% of each individual’s body weight using an Olympic weightlifting bar and associated plate weights. Participants were instructed to stand in the middle of the force platform and stand tall and still for 3 s before each repetition. Participants were instructed to jump for maximum height and to execute a dip or countermovement immediately before the upward propulsion. The following variables were derived from the ground reaction force produced during each CMJ repetition, jump height (cm), peak concentric jump velocity (m/s) and peak concentric force per unit of body weight (N/Kg) using a 400S force plate (Fitness Technologies, Adelaide, Australia) and the associated Ballistic Measurement System software (Innervations, Perth, Australia). Reliability of the CMJ-BW and CMJ-WT was assessed by examining the baseline performance across the two experimental trials for each participant, jump height was found to have a CV of 1.8% for CMJ-BW and 8.0% for CMJ-WT, peak concentric jump velocity was found to have a CV of 5.6% for CMJ-BW and 4.0% for CMJ-WT and peak concentric force was found to have a CV of 2.8% for CMJ-BW and 1.8% for CMJ-WT.

3.3.4 Isometric mid-thigh pull (IMTP)

The IMTP test was performed in Study Three (Chapter Six) in a Smith Machine (Plyopower Technologies, Australia) with the ground reaction force recorded using a 400S force plate (Fitness Technologies, Adelaide, Australia) and the associated Ballistic Measurement System software (Innervations, Perth, Australia). Participants were positioned on the centre of the force platform with the bar set at a height that resulted in a hip angle of between 155 and 165° and a knee angle between 125 and 135°. Participants were instructed to pull an immovable bar as hard and fast as possible and maintain the effort for 5 s. Participants were monitored throughout the effort to ensure no change in hip or knee angle occurred. Participants performed two trials with two min of rest separating each trial with the IMTP peak force per unit of body weight (N/Kg) the criterion variable derived and analysed at baseline, post-exercise and 40 min post-recovery. The average of the maximum force per unit of body weight in each repetition was calculated and used for analysis. Reliability of the IMTP was assessed by examining the
baseline performance across the two experimental trials for each participant, peak force was found to have a CV of 6.1%.

3.4 Body composition measures

3.4.1 Dual energy x-ray absorptiometry (DXA)

Total percentage body fat, fat mass, lean mass, and regional body composition were assessed in Studies Two and Three (Chapters Five and Six) from a full body scan using a narrowed beam DXA (Lunar Prodigy; GE Healthcare, Madison, WI) and were automatically analysed using GE Encore software (12.20 software, GE Healthcare), however the regions of interest were confirmed by the technician. The DXA was calibrated with phantoms each morning before testing as per the manufacturers guidelines. Each scan was completed by the same trained technician following a standardised whole-body DXA protocol which required participants to present to the laboratory in a rested state (no exercise on the morning of the scan), fasted overnight (no food or fluid intake the morning of the scan) and bladder voided. During the scan participants wore minimal clothing (underwear or light shorts) and lay in a supine position on the scanning bed with their hands and feet positioned using foam positioning aids in accordance with guideline specified by Nana, et al. 117

3.4.2 3D body scan

Total body surface area was assessed in Studies Two and Three (Chapters Five and Six) by a 3D body scan (Vitus Smart, Human Solutions; Kaiserslautern) with data analysed using CySlice (v.3.4 software, Headus; Perth). Each scan was completed and analysed by the same trained technician following standardised scan positioning procedures. These procedures required participants to present to the laboratory in a rested state (no exercise on the morning of the scan), fasted overnight (no food or fluid intake the morning of the scan) and bladder voided. During the scan participants wore minimal clothing (underwear or light shorts) and a tight-fitting swimming cap to create a smooth surface on the head and minimise measurement error caused by hair. Participants stood on the scanning platform with their feet 25 cm apart and arms by their sides and abducted with a slight bend in the elbows so that the hands were 4 cm away from their legs in accordance with in-house best practice guidelines utilised by the Australian Institute of Sport.
3.4.3 Anthropometry

A basic anthropometry assessment consisting of a sum of seven skinfolds (Harpenden skinfold calliper, Baty International, England), stretch stature (Harpenden Stadiometer, Baty International, England) and body mass (UC-321, A&D Weighing, Australia) was conducted (Chapters Five and Six) by a level two ISAK Anthropometrist using accepted protocols.\textsuperscript{113,118} Participants wore minimal clothing (underwear or light shorts) and the anthropometry assessment commenced with stature and mass measurements. Thereafter the anthropometrist palpated and marked the location for the seven skinfold sites (subscapular, tricep, bicep, iliac crest, abdominal, medial calf and front mid-thigh) on the right side of the participant’s body. Once marked, the anthropometrist took duplicate measures of each site, however when there was a difference of $\geq 5\%$ between first and second measure, a third measurement was then taken. An average of the closest two measures was reported. The thickness (mm) of each of the seven sites was then added together to provide the sum of seven skinfold value. The Anthropometrist who conducted the measurements has a Typical Error (TE) of 0.61 mm for sum of seven skinfolds, 0.03 kg for body mass and 0.18 cm for height.

3.5 Recovery intervention protocols

3.5.1 Cold water immersion (CWI)

CWI was performed in Studies Two and Three (Chapters Five and Six) in an in-ground cool plunge pool at the Australian Institute of Sport Recovery Centre where participants performed 15 min seated whole body immersion (excluding the head and neck) in 15 ± 0.34 (Study Two), 0.18 (Study Three) °C water, as shown in Figure 3.8. This water temperature was selected based on what is currently utilised in practice by the Australian Institute of Sport.

3.5.2 Hot water immersion (HWI)

HWI was performed in Study Two (Chapter Five) in an in-ground spa at the Australian Institute of Sport Recovery Centre where participants performed 15 min seated whole body immersion (excluding the head and neck) in 38 ± 0.29 °C water, as shown in Figure 3.8. This water temperature was selected based on what is currently utilised in practice by the Australian Institute of Sport.
3.5.3 Control (CON)

CON was performed (Chapters Five and Six) in the same room as the hot and cold pools. Participants were seated and rested passively for 15 min.

Figure 3.8: Water immersion
Chapter Four – Impact of variations in cold water immersion recovery protocols on core temperature change determined by pooled data analysis

Chapter Four includes the below manuscript which has been accepted for publication.

Core temperature responses to cold-water immersion recovery: a pooled-data analysis

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7. School of Exercise and Nutrition Science, Queensland University of Technology, Brisbane, Australia.
8. Department of Physiology, Trinity College Dublin, Ireland.

Journal: International Journal of Sports Physiology and Performance (IJSPP)

Impact Factor: 3.042

Author Contributions

Student contributions to work: Involved in conception of the study, collected data sets from co-authors, collated data for statistician, interpreted statistical analysis, was responsible for writing first draft of the paper including preparation of tables and refinement of figures for journal submission and modified drafts following co-author feedback. Consent to access the raw data utilised in this pooled data analysis was provided by the original authors of each research study.

Conceived and designed the experiment: JS, SH, CG, KS
Provided data from previous research: JS, JM, NV, JP, RD, AD, DC, SH
Collated the data: JS
Analysed the data: JS, KS, CG
Wrote/reviewed the paper: JS, KS, SH, CA, JM, GS, CG, JP, RD, NV, DC, AD
4.1 Abstract

4.1.1 Purpose

To examine the effect of post-exercise cold water immersion (CWI) protocols compared with control (CON), on the magnitude and time-course of core temperature ($T_c$) responses.

4.1.2 Methods

Pooled data analyses were used to examine the $T_c$ responses of 157 participants from previous post-exercise CWI trials in our laboratories. CWI protocols varied with different combinations of temperature, duration, depth and mode. $T_c$ was examined as a double difference ($\Delta\Delta T_c$), calculated as the change in $T_c$ in CWI condition minus the corresponding change in CON. The effect of CWI on $\Delta\Delta T_c$ was assessed using separate linear mixed models across two time components (Component 1: immersion, and Component 2: post-intervention).

4.1.3 Results

Intermittent CWI resulted in a mean decrease in $\Delta\Delta T_c$ that was $0.248 \pm 0.097$ °C (estimate ± SE) greater than continuous CWI during the immersion component ($P = 0.022$). There was a significant effect of CWI temperature during the immersion component ($P = 0.050$), where reductions in water temperature of 1°C resulted in decreases in $\Delta\Delta T_c$ of $0.025 \pm 0.012$ °C. Similarly, the effect of CWI duration was significant during the immersion component ($P = 0.009$), where every 1 min of immersion resulted in a decrease in $\Delta\Delta T_c$ of $0.018 \pm 0.006$ °C. The peak difference in $T_c$ between the CWI and CON interventions during the post-immersion component occurred at 60 min post-intervention.

4.1.4 Conclusion

Variations in CWI mode, duration and temperature, have a significant effect on the extent of change in $T_c$. Careful consideration should be given to determine the optimal amount of cooling before deciding which combination of protocol factors to prescribe.
4.2 Introduction

Cold water immersion (CWI) is a widely practiced recovery modality aiming to reduce fatigue and facilitate post-exercise recovery.\textsuperscript{6} It is thought that the combination of cold temperature and hydrostatic pressure promotes reductions in tissue temperatures and blood flow, facilitating subsequent reductions in thermal and cardiovascular strain, oedema, inflammation and pain.\textsuperscript{6,37} The dominant mechanism by which CWI is believed to be effective for acute recovery is its ability to ameliorate hyperthermia and central nervous system mediated fatigue.\textsuperscript{6,37} Indeed, previous research has attributed the enhanced recovery of maximal voluntary contraction force to faster return of central activation resulting from larger CWI induced reductions in core temperature ($T_c$).\textsuperscript{119} While there is increasing evidence to support the notion that CWI enhances both short- and long-term recovery of performance, particularly for endurance and team sports, there are also several studies that have shown CWI to have either a negligible or detrimental effect on performance.

With consideration of this variance in findings, it may be that CWI is not suitable for all post-exercise contexts, and the exercise mode performed prior to immersion, in addition to the time frame available and the environment in which exercise is performed (e.g. hot vs. cool vs. thermoneutral) are key factors influencing the effectiveness of CWI.\textsuperscript{120,121} Endurance based performance has been shown to be most responsive to CWI; however, there is still considerable variability across studies assessing endurance performance. For example, while a number of studies have found CWI to be effective for maintaining cycling time-trial performance in a subsequent exercise bout performed 40 min to 3 days post-CWI, others observed a decrease in time-trial performance over the same time frame. The factors responsible for this large variation in findings across the current literature are unclear, and as such, there is substantial debate as to the true efficacy of CWI as a recovery strategy.

Variation in the physiological and performance recovery responses to CWI is likely to depend the degree of cooling that can be achieved which is a result of the initial interaction between the protocol utilised and the characteristics of the individual (e.g. body composition, age, gender, ethnicity, etc).\textsuperscript{120} Understanding the optimal degree of cooling is important as too little cooling may cause CWI to be less effective due to limited reductions in muscle temperature ($T_m$) and $T_c$.\textsuperscript{122} Conversely, too much cooling may lead to a reduction in muscle contractile force. Current CWI protocols administered in practice vary in terms of the water temperature, duration, depth and mode of immersion, and the optimal combination of these factors remains
unknown. The interaction between each of these protocol factors is complex and previous research has shown the same degree of Tc change (0.4°C) in response to different CWI protocols (e.g. 5 min, 14°C, whole body immersion vs. 5 min, 10°C, leg only immersion\(^74\)). However, it remains unknown whether the thermal stress applied by the temperature stimulus, the duration of exposure to the cold stimulus, the depth of immersion and body surface area exposed to the cold stimulus, or the change in temperature gradient by moving in and out of the water during intermittent immersion has the greatest impact on Tc responses.

Recently it has been suggested that continuous immersion in water temperatures between 11-15°C for 11-15 min are optimal for reducing muscle soreness.\(^{123}\) However, the most effective approach for reducing Tc and exercise-induced hyperthermia remains unknown, and further research is required to understand how each factor contributes to Tc change. With previous research showing that the change in Tc is related to a change in performance,\(^5,119,124\) it is important to gain a greater understanding of Tc responses as it will enable CWI protocols to be optimised and ultimately improve the restoration of performance for individual athletes. Therefore, the aims of the present study were twofold: 1) to conduct a pooled analysis across a large data set to examine the impact of variability in different CWI protocol factors on Tc change relative to a control condition; and 2) to characterise the time-course of Tc responses to post-exercise CWI both during immersion and post-immersion.

### 4.3 Methods

#### 4.3.1 Study design

This study adopted a pooled analysis approach using data from 157 male participants from 13 previous investigations of post-exercise CWI in our laboratories. Data were assessed using two respective linear mixed models based on different time components. The first component examined the change in Tc between the end of exercise and the end of the CWI/Control (CON) recovery intervention (Component 1: immersion). The second component examined the post-recovery change only and is defined as the difference in Tc between the end of the CWI/CON recovery intervention and each of the available post-intervention time-points (Component 2: post-intervention).
4.3.2 Data sources

Individual de-identified raw data were collated from 13 previous studies by our groups for inclusion in this pooled analysis (Table 4.1). Criteria for inclusion were: 1) use of a cross-over controlled design, 2) included seated passive CON condition, 3) CWI performed post-exercise, 4) measured $T_c$ via rectal thermistor or telemetric pill, and 5) exercise resulted in a significant increase from baseline in mean $T_c$ ($\geq 38.0 ^\circ C$). Studies with missing data (where raw data could not be accessed) or without $T_c$ measures immediately post-exercise and/or post-recovery were excluded (Figure 4.1). There were no specific criteria for type of exercise utilised; however, 11 studies examined cycling and two examined sprint running. Of the 13 studies included, ten are published in academic journals and three in PhD theses.

16 studies considered for inclusion
191 potential participants
3 studies excluded based on;
1) Missing data
2) Post-exercise $T_c \leq 38.0 ^\circ C$

Studies included: 13
Participants included: 157

Figure 4.1: Flow chart on all relevant cold water immersion studies performed in our laboratories and the reason for exclusion
Table 4.1: Data Sources

<table>
<thead>
<tr>
<th>Study number</th>
<th>Reference</th>
<th>Number of participants</th>
<th>CWI condition(s)</th>
<th>CON condition</th>
<th>T&lt;sub&gt;c&lt;/sub&gt; measurement time-points</th>
<th>Offset (EndEx to Rec0)</th>
<th>Ambient temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Peiffer, et al.&lt;sup&gt;39&lt;/sup&gt;</td>
<td>12</td>
<td>5 min</td>
<td>14 °C Chest C</td>
<td>Rectal EndEx EndRec PostRec: 5, 10, 20, 30, 40 min</td>
<td>25 min</td>
<td>40 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 min</td>
<td>14 °C Chest C</td>
<td>Rectal EndEx EndRec PostRec: 5, 10, 20, 30, 40 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Peiffer, et al.&lt;sup&gt;31&lt;/sup&gt;</td>
<td>8</td>
<td>20 min</td>
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<td>7.5 min</td>
<td>32 °C</td>
</tr>
<tr>
<td>3</td>
<td>Peiffer, et al.&lt;sup&gt;9&lt;/sup&gt;</td>
<td>10</td>
<td>5 min</td>
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<td>Rectal EndEx EndRec PostRec: 5 min</td>
<td>5 min</td>
<td>35°C</td>
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<tr>
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<td>20</td>
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<td>22°C</td>
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<td>9</td>
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<td>10 °C Chest C</td>
<td>Sensor EndEx</td>
<td>10 min</td>
<td>32 °C</td>
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<tr>
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<td>12</td>
<td>20 min, seated, room temperature 32 °C</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td><strong>Condition 1:</strong></td>
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</tr>
<tr>
<td></td>
<td>5 min (5x 1 min in;2 min out)</td>
<td>10 °C</td>
<td>Neck I</td>
<td>EndEx</td>
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<td></td>
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<td>Neck C</td>
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<td>5 min (5x 1 min in;2 min out)</td>
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<tr>
<td>7</td>
<td>Pointon, et al. 7</td>
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<tr>
<td>8</td>
<td>Vaile, et al. 7</td>
<td>12</td>
<td>14 min, seated, room temperature not reported</td>
<td>Rectal</td>
<td></td>
<td></td>
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<td>Neck C</td>
<td>EndEx</td>
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<td>Condition 2:</td>
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<td>PostRec:</td>
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<td>15 min</td>
<td>15 °C</td>
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<td>PostRec: 5, 30, 60, 90</td>
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<td>120, 150, 180, 210, 240</td>
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<td>Stephens (Chapter 5)</td>
<td>27</td>
<td>15 min</td>
<td>15 °C</td>
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<td>EndEx</td>
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<td>15 min</td>
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<td>120, 150, 180, 210, 240</td>
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<tr>
<td>11</td>
<td>Versey</td>
<td>9</td>
<td>14 min</td>
<td>15 °C</td>
<td>Neck</td>
<td>C</td>
<td>EndEx</td>
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<td></td>
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<td>14 min</td>
<td>15 °C</td>
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<td>12</td>
<td>Crampton</td>
<td>10</td>
<td>30 min</td>
<td>15 °C</td>
<td>Waist</td>
<td>C</td>
<td>EndEx</td>
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<td></td>
<td></td>
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<td>30 min</td>
<td>8 °C</td>
<td>Waist</td>
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<td>Sensor</td>
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<td>EndEx</td>
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<td>PostRec: 5, 30, 60, 90</td>
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<td></td>
<td>120, 150, 180, 210, 240</td>
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<tr>
<td>13</td>
<td>Halson, et al.</td>
<td>11</td>
<td>3 min</td>
<td>11 °C</td>
<td>Neck</td>
<td>I</td>
<td>EndEx</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 min</td>
<td>11 °C</td>
<td></td>
<td>Rectal</td>
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<td>(3x 1 min in</td>
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<td></td>
<td>EndRec</td>
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<td>;2min out)</td>
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</table>

CWI = cold water immersion, CON = control, C = continuous, I = intermittent, Tc = core temperature, EndEx = immediately post-exercise, Rec0 = start of recovery intervention EndRec = immediately post-recovery, PostRec = post-recovery intervention
4.3.3 Participants

De-identified raw data were extracted from 13 studies, providing data on 157 trained male participants (Table 4.2). Participants across all studies were classified as well-trained with 94 identifying as predominantly participating in cycling or triathlon, 29 in team sports, leaving 36 with an unspecified sporting background.

Table 4.2: Mean participant characteristic in each study.

<table>
<thead>
<tr>
<th>Study number</th>
<th>Reference</th>
<th>Height (cm)</th>
<th>Weight (cm)</th>
<th>Age (yrs)</th>
<th>VO₂ max (ml.kg.min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Peiffer²⁹</td>
<td>181.0 ± 6.0</td>
<td>77.9 ± 6.6</td>
<td>27.0 ± 7.0</td>
<td>61.7 ± 5.0</td>
</tr>
<tr>
<td>2</td>
<td>Peiffer³¹</td>
<td>178.8 ± 5.4</td>
<td>77.1 ± 6.5</td>
<td>29.3 ± 3.0</td>
<td>64.0 ± 5.7</td>
</tr>
<tr>
<td>3</td>
<td>Peiffer⁹</td>
<td>182.6 ± 7.0</td>
<td>80.3 ± 9.7</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>4</td>
<td>Stephens¹²⁴</td>
<td>181.9 ± 7.9</td>
<td>78.7 ± 9.6</td>
<td>32.1 ± 7.5</td>
<td>59.7 ± 6.2</td>
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<tr>
<td>5</td>
<td>Minett¹¹⁹</td>
<td>183.0 ± 7.0</td>
<td>78.7 ± 8.1</td>
<td>21.0 ± 2.0</td>
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</tr>
<tr>
<td>6</td>
<td>Vaile¹³⁰</td>
<td>181.3 ± 4.6</td>
<td>76.4 ± 7.1</td>
<td>32.8 ± 3.8</td>
<td>69.9 ± 4.8</td>
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<tr>
<td>7</td>
<td>Pointon</td>
<td>179.6 ± 3.8</td>
<td>78.9 ± 6.3</td>
<td>19.9 ± 1.1</td>
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</tr>
<tr>
<td>8</td>
<td>Vaile⁷</td>
<td>176.6 ± 4.5</td>
<td>68.8 ± 7.2</td>
<td>32.2 ± 4.3</td>
<td>68.8 ± 3.6</td>
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<tr>
<td>9</td>
<td>Dunne¹²⁶</td>
<td>177.0 ± 5.0</td>
<td>68.0 ± 5.0</td>
<td>29.0 ± 7.0</td>
<td>62.1 ± 5.0</td>
</tr>
<tr>
<td>10</td>
<td>Stephens¹²⁷</td>
<td>181.7 ± 7.5</td>
<td>83.2 ± 11.9</td>
<td>32.7 ± 7.9</td>
<td>55.8 ± 7.9</td>
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<tr>
<td>11</td>
<td>Versey¹²⁸</td>
<td>177.2 ± 5.3</td>
<td>74.3 ± 8.4</td>
<td>29.9 ± 5.6</td>
<td>62.0 ± 5.2</td>
</tr>
<tr>
<td>12</td>
<td>Crampton¹²⁹</td>
<td>184.0 ± 5.0</td>
<td>86.0 ± 8.6</td>
<td>26.0 ± 5.0</td>
<td>54.6 ± 7.4</td>
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<tr>
<td>13</td>
<td>Halson⁶⁸</td>
<td>182.2 ± 4.2</td>
<td>72.1 ± 4.0</td>
<td>23.8 ± 1.6</td>
<td>71.3 ± 1.2</td>
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</tbody>
</table>

n/a = information not available

4.3.4 Cold water immersion protocol combinations

CWI protocols varied across studies, with seven different temperatures, eight immersion durations, three depths and two modes of immersion utilised (Table 1), making a total of 336
possible combinations of which 16 were utilised. Of the 13 studies included, nine studies used just one CWI protocol, two studies used two protocols, one study included three protocols, and another study used four different protocols giving a total of 20 within-study-protocol combinations. Of these protocols, four were used in two studies so that there were only 16 of the 336 possible CWI protocols represented across the 13 studies. Further, there were only 15 (out of a possible 56) combinations of duration and temperature used, with just one combination used at more than one immersion depth. Additionally, all 15 of these combinations were associated with just one of the two modes, continuous or intermittent, resulting in partial confounding between the four components of the CWI protocols so that it is not possible to completely separate the effects of the various (protocol) factors. For analysis and to allow comparisons between studies, immersion depth was converted into a predicted body-surface-water-contact area of 1.3 m$^2$ for waist-depth, 1.6 m$^2$ for chest-depth, and 1.8 m$^2$ for neck-depth based on normative measurements of an average, and therefore comparable, male. The offset time between the end of exercise and the commencement of CWI also varied, and there were seven different offset times used across the 13 studies (Table 4.1).

4.3.5 Core temperature ($T_c$)

$T_c$ was either measured by rectal thermister or by sensor telemetry. $T_c$ was measured at different time-points across the 13 studies (Table 4.1), including immediately post-exercise, immediately post-recovery (0 min) and at 13 post-recovery time-points (5, 10, 15, 20, 30, 40, 60, 90, 120, 150, 180, 210, 240 min post-intervention). Two of the studies recorded just two $T_c$ values for each participant; one at the end of exercise and the other at the end of CWI, and therefore were only included in the immersion component analysis. The other 11 studies recorded $T_c$ values at additional times following the completion of CWI and were therefore included in the post-intervention component analysis. One study controlled post-exercise $T_c$ to ensure it was equal across participants and trials, while the remaining 12 studies did not attempt to control post-exercise $T_c$. Regardless, there was no significant difference between trials (CWI vs CON) for each participant, as determined by initial t-test analysis. The $T_c$ response was calculated in each of the models as a double difference ($\Delta\Delta T_c$), whereby the change in $T_c$ in the CWI condition minus the corresponding difference under the control condition relative to post-exercise in Component 1 and immediately post-recovery in Component 2, (e.g. $\Delta\Delta T_c = (CWI\ \text{post-exercise} \ T_c - \text{CWI \ post-recovery} \ T_c) - (\text{CON \ post-}$
exercise $T_c$ – CON post-recovery $T_c$). A negative $\Delta \Delta T_c$ indicates that the change in $T_c$ is greater in the CWI condition compared to the control.

### 4.4 Statistical analysis

The statistical analysis consisted of two, distinct components. The first component (immersion) considered the $\Delta \Delta T_c$ changes from the end of exercise to the end of the recovery treatment, while the second component (post-intervention) considered the $\Delta \Delta T_c$ changes following the recovery intervention. For each component, a linear mixed model was used with CWI protocols (combination of duration, temperature, depth and mode) and the offset from the end of exercise to the start of the CWI treatment treated as a fixed effects and either study-protocol (i.e. the different protocols within a study were essentially treated as being different studies) or subject as random effects for components 1 and 2, respectively. Five of the 11 studies with data following the CWI treatment period included more than one post-CWI observation and the models fitted to these data made allowance for possible autocorrelation within participants. To fit these models, it was necessary to treat the participants that used more than one protocol (within a study) as though they were different participants. In addition to the effect of CWI treatment, it was also of interest to evaluate how the $\Delta \Delta T_c$ varied with time, post-recovery. When this time was fitted as a (fixed effect) factor (only 13 time points were used in the studies), the relationship was deemed appropriate to then subsequently model using regression splines. All models were fitted using the lme or gamm components of the mgcv package available in R. The significance level was $P < 0.05$ and data are reported as mean ± standard deviation or estimate ± standard error.

### 4.5 Results

#### 4.5.1 Component 1 – Immersion

Across all participants average post-exercise $T_c$ was $38.56 \pm 0.60$ °C and immediately post-intervention was $37.72 \pm 0.53$ °C. The effects of CWI time, temperature and mode are illustrated in Figure 4.2 which gives the estimated overall responses for each of the 20 study-protocol combinations used in the 13 studies. Intermittent CWI results in a significantly ($P =$...
0.022) greater decrease in ΔΔTc 0.248 ± 0.097 °C (estimate ± SE) than that obtained with continuous CWI. The effect of CWI temperature can be described by a significant (P = 0.050) linear regression with a coefficient of 0.025 ± 0.012 °C. That is, for each reduction in CWI temperature of 1°C, ΔΔTc is estimated to decrease on average by 0.025 °C. The effect of CWI duration was significant (P = 0.006), with a decrease of 0.018 ± 0.006 °C ΔΔTc for each additional minute of CWI immersion. Neither depth (P = 0.185) nor offset time (P = 0.900) had a significant effect on ΔΔTc.

The inclusion of the study-protocol in the model had a minimal effect on the parameter estimates, though it did result in slight increases in the standard errors and hence slight increases in the p-values. The residual standard deviation, which includes the between-subject variation not accounted for by the fitted model, and indicates the variation that was observed between the changes in individual participants, was estimated to be 0.444 °C.

Figure 4.2: Estimated responses for each of the 20 study-protocol combinations used in the 13 studies. Numbers next to data points = water temperature. ΔΔTc = Change in Tc in CWI condition minus change in Tc in CON condition.
4.5.2 Component 2 – Post-recovery

The effect of offset time was significant (P = 0.002), with an increase of 0.011 °C $\Delta\Delta T_c$ for each minute increase in offset time. Further, the effect of post-recovery time was also significant (P < 0.001) and was adequately described by a cubic regression spline. Specifically, peak difference between CWI and CON occurred at ~60 min post-intervention; following this $\Delta\Delta T_c$ slowly increased until there was no impact of the intervention (Figure 4.3). Also displayed in Figure 4.3 are estimates of the effect of post-recovery time when it was treated as a factor (with 13 levels, the number of different times used in the studies). Other effects such as CWI type (intermittent or continuous), duration, temperature and depth were also evaluated, but none of them made a (statistically) significant contribution.

The inclusion of within subject autocorrelation in the model had an appreciable effect on the parameter estimates with the autocorrelation being highly significant (P < 0.001). The residual standard deviation, which includes within-subject variation not accounted for by the fitted model, was estimated to be 0.358 °C.
Figure 4.3: Parameter estimates and fitted spline with 95% confidence limits for the change in $T_c$ from end of intervention to each of the post-intervention time points. $\Delta \Delta T_c =$ Change in $T_c$ in CWI condition minus change in $T_c$ in CON condition.

4.6 Discussion

The present study aimed to understand the implications of varying the temperature, duration, depth and mode of CWI protocols on $T_c$, and to identify the ensuing time-course of $T_c$ responses based on these post-exercise CWI protocol variations. The main findings were: 1) that intermittent protocols resulted in a significantly greater decrement in $T_c$ compared to continuous protocols for the $T_c$ change during immersion; 2) decreasing water temperature and increasing duration of CWI resulted in a significant decrease in $\Delta \Delta T_c$ during immersion; 3) the longer the offset time (end of exercise to immersion commencement), the smaller the change in $T_c$ post-recovery; and 4) the peak difference in $T_c$ between CON and CWI protocols occurred at ~60 min post-recovery, irrespective of protocol mode.

Reported post-exercise CWI protocols vary substantially,\textsuperscript{120,123} and while CWI is widely utilised by athletes, a lack of consensus as to the best protocols for different sport/athlete scenarios remains.\textsuperscript{33} Accordingly, the present study combined the data from a range of studies representing the variety of protocols currently utilised to determine the impact of different combinations and interaction of these factors on the change in $T_c$. One of the major findings of the present study was that intermittent CWI protocols appear to be more effective in lowering $T_c$ compared to continuous CWI. It may be postulated that the lower $T_c$ observed, on average, in response to intermittent CWI might be related to the frequent change in thermal gradient occurring each time the participant moves between the cold water and the warmer air. This frequent change may have led to repeated reactive hyperaemia responses where blood flow increases when the participant moves out of the pool after a period of cold-induced vasoconstriction and ischemia which occurs during immersion.\textsuperscript{45} This theory is supported by the findings of and who found that following removal from CWI, vasodilation occurred in the extremities and greater conductive heat transfer occurred due to the return of cooler blood to the central circulation. Nevertheless, as only three studies utilised intermittent protocols, the conclusions which can be drawn from these data need to be confirmed by future research.

Often in practical settings, the duration and depth of CWI are determined by the water temperature based on athlete tolerance; thus, these variables were also examined in the present
study given their ecological interactions in many protocols. Although it has been suggested that the physiological changes in response to post-exercise CWI are temperature dependent, the way these factors interact with each other and which factor has the greatest impact on $T_c$ responses remains unknown.\textsuperscript{120} Both temperature and duration were found to have a highly significant impact on $\Delta T_c$. The current study found that CWI temperature led to a decrease in $\Delta T_c$ of 0.025 °C for every 1 °C reduction in water temperature, and that CWI duration led to a reduction in $\Delta T_c$ of 0.018 °C for every additional minute of immersion time. Collectively, colder water temperatures and greater immersion durations lead to a greater reduction in $T_c$ compared to an equivalent duration CON. However, such an effect was only observed for continuous immersion protocols, as no evidence of a duration effect was apparent for intermittent protocols given the small range of intermittent protocols included in the analyses. The depth of immersion was not significant and highly confounded with the other protocol factors. Increasing immersion depth is believed to enhance responses to CWI by increasing hydrostatic pressure as well as exposing a greater body surface area for thermal exchange via convection to occur.\textsuperscript{120} The impact of hydrostatic pressure was recently examined by comparing seated versus standing CWI, with no significant difference reported between the two conditions, suggesting water temperature may be of greater importance.\textsuperscript{137} Given the absence of studies examining the effect of different immersion depths on $T_c$ responses to post-exercise CWI, further research is required to fully determine the impact of varying CWI depth. Post-exercise CWI has been shown to significantly reduce $T_c$; however, the extent of this reduction is highly variable, and the time-course of change remains to be fully elucidated.\textsuperscript{120} The present study examined the change in $T_c$ during and post-immersion as two separate components as it was recognised that the rate of $T_c$ change would be vastly different depending on the thermal environment the body is placed in. The present study found that the sooner CWI is commenced post-exercise the greater the reduction in post-immersion $T_c$ will be. This may be due to $T_c$ and blood flow being elevated at the end of exercise, therefore, increasing the thermal gradient between the body and the water and thermal exchange between blood and body tissues. It was also found that when examining $T_c$ change post-recovery, the greatest difference between CWI and CON occurred 60 min post-recovery (Figure 4.2). This novel finding highlights the importance of this time period post-immersion, and it highlights the potentially negative effect of a hot shower post-immersion, which is a common practice of some athletes. However, with only three studies examining $T_c$ change for $\geq$ 60 min post-
immersion, the estimates of $\Delta \Delta T_c$ become weaker as time increases, potentially limiting the strength of conclusions which can be drawn.

This prolonged decrease in $T_c$ after CWI may have practical implications for repeat-performance and should be considered when prescribing protocols. It is hypothesised that the optimal protocol parameters will vary depending on recovery needs of the athlete, which will be determined by the specific type of fatigue (e.g. central nervous system fatigue, cardiovascular fatigue, etc.), time-frame available and type of performance (e.g. endurance vs sprint) required.\textsuperscript{6,120} It is also important to consider the environmental conditions. For example, performing CWI during a short time-frame between endurance tasks may provide pre-cooling benefits for subsequent exercise, particularly when environmental conditions are warm or hot. However, when performance requires maximal contractions and the time-frame between repeat performances is short, CWI induced changes in body temperature will likely reduce muscular performance.\textsuperscript{120,123}

Future studies should focus on determining the exact degree of change in $T_c$ that leads to an optimal cooling effect for subsequent performance and how different CWI protocol factors work towards inducing this $T_c$ change. The residual standard deviations were estimated to be 0.444 °C and 0.358 °C for components 1 and 2, respectively. Compared to the estimated effects of CWI, these values are relatively large which means that, while various effects have been found, on average, to be statistically significant, there is a lot of additional variation between participants (for component 1) and within participants (for component 2) so that it is not yet possible to deduce how individual athletes will respond to CWI.

4.7 Conclusion

The present pooled-data analysis study builds on a previous meta-analysis\textsuperscript{138} by examining individual responses to a range of CWI protocols and highlights the fact that responses to post-exercise CWI are highly variable and are impacted by a myriad of factors. It is not solely the dose of cooling provided by the combination of CWI temperature, duration, depth and mode that impact these responses. Other factors such as laboratory/environmental conditions, differences in exercise induced thermoregulatory stress, offset differences (i.e. time between end of exercise and start of CWI) and individual participant differences (e.g. body composition, age, gender and ethnicity) also impact responses and may explain much of the variation in the current literature. The relatively homogenous cohort examined in this pooled analysis acts to
delimit several of these potentially confounding factors (e.g. gender, age, body composition), yet this may also limit the applicability of findings to other populations. The large number of factors impacting the cooling response makes attempting to predict the optimal “dose” of CWI quite difficult, especially when many combinations of factors have not been tested. Nevertheless, this study has drawn on a large data set to provide some clarity around the influence of CWI protocol mode, temperature, duration and offset differences on $T_c$ response. An understanding of how variations in these factors impact temperature change will enable future researchers to better prescribe CWI protocols, and ultimately facilitate the optimisation of performance recovery.
Chapter Five - Effect of body size and composition on temperature and blood flow responses to post-exercise hydrotherapy

Chapter five includes the below publication:

Influence of body composition on physiological responses to post-exercise hydrotherapy.

Jessica M. Stephens¹,², Shona Halson², Joanna Miller², Gary Slater¹ and Christopher D. Askew¹

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2018, Volume 36, Issue 9, Pages 1044-1053.

Impact Factor (2016): 2.539

Author Contributions

Student contribution to work: Involved in the conception of the study, collected all data, analysed and interpreted data, was responsible for writing the first draft of the manuscript including preparation of all figures and tables and modified drafts following co-author recommendations.

Conceived and designed the experiment: JS, SH, JM, GS, CA
Performed the experiment: JS, JM
Analysed the data: JS, CA, SH, JM
Wrote/reviewed the paper: JS, CA, SH, JM, GS
5.1 Abstract

5.1.1 Purpose

This study examined the influence of body composition on temperature and blood flow responses to post-exercise cold water immersion (CWI), hot water immersion (HWI) and control (CON).

5.1.2 Methods

Twenty-seven male participants were stratified into three groups: 1) low mass and low fat (LM-LF); 2) high mass and low fat (HM-LF); or 3) high mass and high fat (HM-HF). Experimental trials involved a standardised bout of cycling, maintained until core temperature reached 38.5 °C. Participants subsequently completed one of three 15-min recovery interventions (CWI, HWI, or CON). Core, skin and muscle temperatures, and limb blood flow were recorded at baseline, post-exercise, and every 30 min following recovery for 240 min.

5.1.3 Results

During CON and HWI there were no differences in core or muscle temperature between body composition groups. The rate of fall in core temperature following CWI was greater in the LM-LF (0.03 ± 0.01 °C/min) group compared to the HM-HF (0.01 ± 0.001 °C/min) group (P = 0.002). Muscle temperature decreased to a greater extent during CWI in the LM-LF and HM-LF groups (8.6 ± 3.0°C) compared with HM-HF (5.1 ± 2.0 °C, P < 0.05). Blood flow responses did not differ between groups.

5.1.4 Conclusion

Differences in body composition alter the thermal response to post-exercise CWI, which may explain some of the variance in the responses to CWI recovery.
5.2 Introduction

The use of hydrotherapy, particularly cold water immersion (CWI), has become common practice for athletes in an attempt to enhance recovery from training and competition. While there is growth in the evidence to support such strategies, there remains disparity in protocols utilised and variability in the reported effectiveness of CWI on performance recovery. Similarly, hot water immersion (HWI) is widely utilised, however there has been limited investigation into its efficacy for performance recovery, and findings to date have been mixed. This variability presents a challenge in the practical application of hydrotherapy, highlighting the need to better understand the physiological mechanisms responsible for performance recovery, and the individual characteristics that impact upon the physiological responses.

Guidelines for post-exercise hydrotherapy have a ‘one size fits all’ approach, as athletes often complete the same protocol regardless of individual characteristics. It is important to recognize that individual athletes may have vastly different physiques which are likely to affect the physiological responses to hydrotherapy. Physique traits such as body fat, muscle mass and body surface area all influence the thermal responses during exposure to extreme environments. For example, subcutaneous fat has an inverse relationship with the rate of decline in body temperature during CWI, and thermal insulation is increased in individuals with a greater volume of muscle tissue.

Our understanding of the impact of body characteristics on thermal responses to water immersion comes largely from experimental investigations where the study conditions have been vastly different to the water immersion protocols used for recovery in sport. For example, CWI protocols are typically conducted in 5-20 °C water for 3-20 min and HWI in water ≥ 36 °C for 10-24 min. Whereas previous research that has aimed to examine the effect of body composition on thermal responses to CWI has used different CWI water temperature ranges 17-28 °C and much longer immersion durations 90 min to 10 h. These studies have also been limited by small participant numbers (n=2-6), and the use of sub-optimal methods that lack sensitivity for determining body temperature (e.g. tympanic temperature), and body composition (e.g. bioelectrical impedance, surface anthropometry). Most importantly, the aforementioned studies have been conducted under resting conditions and have not examined the impact of body composition on thermal and physiological responses in the post-exercise state when thermal load is increased.
The performance recovery benefits of hydrotherapy depend largely on the magnitude of temperature change and associated physiological perturbations. A better understanding of the impact of body composition on these factors will aid in the optimisation of recovery protocols, and reduce the risk of inadvertent “over-cooling” or “over-heating” which pose a potential risk to the performance and health of athletes. Therefore, the purpose of the present study was to compare thermal and physiological responses to both post-exercise CWI and HWI between individual athletes that differ in body mass and composition.

5.3 Methods

5.3.1 Participants

105 active males underwent initial body composition assessment by dual energy x-ray absorptiometry (DXA) to determine suitability for inclusion based on the following criteria: male, aged 18-45 y, training a minimum of 5 h per week, minimum cycling peak power output at VO$_{2}$max (PPO) of > 250 Watts, and body composition characteristics that corresponded with one of the group criteria below. 36 males met these criteria, of whom 27 agreed to participate (Table 5.1) and were stratified into one of the following groups based on normative athlete characteristics:\textsuperscript{144} 1) low mass and low fat (LM-LF) BMI $\leq$ 21.0 kg/m$^2$ and body fat percentage $\leq$ 13.0% (n=9); 2) high mass and low fat (HM-LF) BMI $\geq$ 25.0 kg/m$^2$ and body fat percentage $\leq$ 13.0% (n=9); or 3) high mass and high fat (HM-HF) BMI $\geq$ 25.0 kg/m$^2$ and body fat percentage $\geq$ 18.0% (n=9). Participants were non-smokers, free of illness/injury and provided written informed consent prior to participation. Female participants were not considered for this study due to the repeat trial design of the study and the potential confounding effects of menstrual cycle phase on core temperature and thermal sensation.\textsuperscript{104} The study was approved by the institutional Human Research Ethics Committees.
Table 5.1: Participant characteristics

<table>
<thead>
<tr>
<th></th>
<th>LM-LF (n = 9)</th>
<th>HM-LF (n = 9)</th>
<th>HM-HF (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs.)</td>
<td>31.4 ± 6.5</td>
<td>29.2 ± 9.3</td>
<td>37.0 ± 5.4</td>
</tr>
<tr>
<td>VO2_{max} (L/min)</td>
<td>4.5 ± 0.5</td>
<td>4.7 ± 0.5</td>
<td>4.7 ± 0.6</td>
</tr>
<tr>
<td>VO2_{max} (ml.gk.min)</td>
<td>63.4 ± 8.0</td>
<td>55.9 ± 5.6</td>
<td>51.0 ± 5.2</td>
</tr>
<tr>
<td>PPO (W)</td>
<td>314.9 ± 40.3</td>
<td>316.4 ± 42.7</td>
<td>312.1 ± 36.5</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>185.7 ± 8.2</td>
<td>180.7 ± 5.7</td>
<td>179.3 ± 4.7</td>
</tr>
<tr>
<td>Total mass (kg)</td>
<td>71.8 ± 6.2*</td>
<td>85.2 ± 6.0</td>
<td>91.6 ± 12.3</td>
</tr>
<tr>
<td>Percent body fat (%)</td>
<td>9.1 ± 1.9*</td>
<td>11.7 ± 1.4#</td>
<td>24.8 ± 5.2</td>
</tr>
<tr>
<td>Fat mass (kg)</td>
<td>6.4 ± 1.4*</td>
<td>9.6 ± 1.3#</td>
<td>22.3 ± 6.8</td>
</tr>
<tr>
<td>Total lean mass (kg)</td>
<td>63.4 ± 5.8*</td>
<td>72.1 ± 5.6</td>
<td>66.0 ± 7.5</td>
</tr>
<tr>
<td>Left leg lean mass (kg)</td>
<td>10.8 ± 1.2*</td>
<td>12.9 ± 1.1#</td>
<td>11.2 ± 1.5</td>
</tr>
<tr>
<td>Left leg fat mass (kg)</td>
<td>1.17 ± 0.28**</td>
<td>1.82 ± 0.35#</td>
<td>3.50 ± 0.76</td>
</tr>
<tr>
<td>BMI (kg/m^2)</td>
<td>20.8 ± 0.6*+</td>
<td>26.1 ± 0.7#</td>
<td>28.3 ± 1.7</td>
</tr>
<tr>
<td>Sum 7 (mm)</td>
<td>46.8 ± 5.7*</td>
<td>55.5 ± 4.2#</td>
<td>113.5 ± 35.9</td>
</tr>
<tr>
<td>BSA (m^2)</td>
<td>1.93 ± 0.15</td>
<td>2.03 ± 0.13</td>
<td>2.07 ± 0.17</td>
</tr>
<tr>
<td>BSA:M (m^2/kg)</td>
<td>0.027 ± 0.001*+</td>
<td>0.024 ± 0.001#</td>
<td>0.023 ± 0.001</td>
</tr>
</tbody>
</table>

LM-LF = low mass and low fat, HM-LF = high mass and low fat, HM-HF = high mass and high fat. VO2_{max} = maximal oxygen uptake, PPO = peak power output, BMI = body mass index, Sum 7 = sum of 7 skinfolds, BSA = body surface area, BSA:M = body surface area to mass ratio. * Significant difference between LM-LF & HM-HF, # Significant difference between HM-LF & HM-HF, ** Significant difference between LM-LF & HM-LF. (p < 0.05).

5.3.2 Experimental design

Participants attended the laboratory on five occasions. The first visit involved body composition assessments including DXA (Lunar Prodigy; GE Healthcare, Madison, WI) and three dimensional body scan (Vitus Smart XXL, Human Solutions; Kaisersalutern) for the determination of body composition characteristics using previously described procedures. The second visit included an anthropometry assessment (skinfolds, height and weight), maximal incremental cycling test for the determination of VO2_{max} and PPO, and familiarisation with experimental procedures.
Three experimental trials were then performed in a randomised counterbalanced crossover design, separated by a minimum of 7 days (Figure 5.1). Participants refrained from exercise, caffeine and alcohol consumption for 24 h, and fasted for 2 h prior to each trial. Food intake and exercise diaries were used to ensure consistency across the trials. Trials commenced with baseline measures of core ($T_c$) and skin ($T_{sk}$) temperature, thermal sensation, heart rate (HR), blood pressure (BP) and limb blood flow followed by a standardised bout of cycling; 5 min warm up at 40% PPO, followed by a work period at 75% PPO, maintained until $T_c$ reached 38.5 °C. Immediately following exercise an intramuscular temperature probe was inserted for measures of muscle temperature ($T_m$). Participants then completed either: i) CWI, 15 min at 15°C; ii) HWI, 15 min at 38 °C; or iii) control (CON), 15 min non-immersed seated passive rest, commencing exactly 15 min post-exercise. Immersions were performed while seated with water to the level of the neck and protocols were chosen based on current practice. Post-recovery measures were conducted at 5 min, then every 30 min until 240 min post-recovery. During the 240 min post-recovery period participants passively rested in a supine position with the exception of a 10 min seated meal break and 5 min bathroom breaks every 60 min. Hydration status on the day of testing was checked by analysing upon waking urine specific gravity and was consistent across trials. Standardised fluid and meals (350ml Up & Go Energise, Toast and Jam) were consumed between the 30 and 60 min post-recovery measures. All testing was performed in a temperature controlled laboratory (23.1 ± 1.2°C, 37.6 ± 10.7% RH).
5.4 Measures

5.4.1 Body temperatures (core, skin and muscle) and thermal sensation.

Core temperature ($T_c$) was measured using a disposable rectal thermometer (Monatherm, Mallinckrodt, USA). Skin temperature ($T_{sk}$) was measured at four sites (chest, arm, thigh and calf) using iButton (DS1922L, Maxim Integrated Products Inc., USA) temperature sensors and mean $T_{sk}$ was calculated as $T_{sk} = 0.3 \times (T_{chest} + T_{arm}) + 0.2 \times (T_{thigh} + T_{leg})$. Muscle temperature ($T_m$) was measured in the vastus lateralis. A flexible teflon multi-sensor temperature probe (T-336, Physitemp Instruments, USA) was inserted 3 cm below subcutaneous fat, verified using B-mode ultrasound (Terason t3000 Ultrasound System, Teratech Corporation, USA). Each probe consisted of three thermocouples positioned at 1, 2, and 3 cm depth. $T_m$ data were wirelessly transmitted (Thermes USB Data Acquisition System, 112 Teratech Corporation, USA).
Physitemp Instruments, USA) and logged every 10 s (DASY Lab 10.0.1, Measurement Computing, USA). A mean of all three depths was calculated for each post-exercise time-point. Tc and Tm responses were described as: recovery-drop, calculated as the difference from the end of exercise to the end of the recovery (immersion) period; peak drop – the largest fall following exercise; and after-drop – the largest fall following the end of the recovery (immersion) period. Perceived thermal sensation was measured on a scale of zero (unbearably cold) to eight (unbearably hot).

5.4.2 Forearm and calf blood flow, blood pressure and heart rate

Participants lay supine with the right arm and both legs raised on foam blocks above the level of the heart. Mercury-in-rubber strain gauges (Hokanson, USA) were placed around maximal girth of the right calf and on the forearm 5 cm distal to the olecranon process. Blood flow was assessed in triplicate at the arm and then the leg, with 10 s separating each measurement. Measures were averaged to provide a single measure of leg and arm blood flow at each time-point, and the leg-to-arm blood flow ratio was calculated as described previously. The Typical Error (TE) in our laboratory for arm blood flow was 0.76 ml.100ml⁻¹.min⁻¹ and leg blood flow was 0.72 ml.100ml⁻¹.min⁻¹. Brachial blood pressure (BP) was measured between arm and leg blood flow measures (Omron BP791IT, Omron Healthcare, USA). Heart rate (HR) was continuously logged throughout the trial (S810i, Polar, Finland).

5.5 Statistical Analysis

Physiological responses were initially explored using a three-way (body composition group x recovery intervention x time) mixed analysis of variance (ANOVA) to confirm the presence of the expected differences between recovery conditions. Where there were significant main effects or interactions for recovery condition, further mixed two-way (body composition group x time) ANOVA were carried out to address the primary aim of the study and determine the presence of body composition effects during each of the recovery conditions. Temperature after-drop, peak-drop and recovery-drop were assessed using a two-way (body composition group x recovery condition) mixed ANOVA. Participant characteristics and exercise responses were compared between body composition groups using a one-way analysis of variance (ANOVA). Where significant main effects or interactions were detected, post-hoc analysis was performed using Tukey’s HSD procedure. Pearson product-moment correlation was used
to assess relationships between body composition characteristics and change in core and muscle temperatures. Correlations (r) were interpreted against the following criteria: r < 0.1 trivial, 0.1-0.3 small, 0.3-0.5 moderate, 0.5-0.7 large, 0.7-0.9 very large, and > 0.9 almost certain. The significance level was P < 0.05 and data are reported as mean ± standard deviation or r ± 90% confidence limits for correlations. Statistical analyses were conducted using SPSS computer software (Version 19.0, SPSS Inc., Illinois, USA).

5.6 Results

5.6.1 Participant characteristics, performance and HR

All participants had similar (P ≥ 0.05) VO_2 max/PPO characteristics (Table 1) and exercise duration for T_c to reach 38.5 °C was not different between body composition groups or across recovery conditions (CON: LM-LF 29:38 ± 11:31, HM-LF 34:49 ± 07:07, HM-HF 32:17 ± 09:46; CWI: LM-LF 29:33 ± 09:15, HM-LF 33:47 ± 08:28, HM-HF 33:18 ± 07:16; HWI: LM-LF 28:02 ± 09:41, HM-LF 37:18 ± 05:55, HM-HF 35:06 ± 08:13 min:ss; P > 0.05). There was a significant recovery effect (P = 0.006) and a recovery condition x time interaction (P = 0.0001) for HR. HR was significantly different between the CWI and CON/HWI trials (P = 0.0001) and between CON and HWI (P = 0.035). HR was not different between groups at any time point throughout CON (P =0.261) or CWI (P = 0.212) trials. During the HWI trial there were significant differences between groups at different time points (P = 0.04), HR was significantly higher in the HM-LF group than the LM-LF group at 5-10 min of immersion, and 35 min post-exercise (P < 0.05). Additionally, HR was lower in the LM-LF group compared to the HM-HF group at 5-10 min of immersion, and at 35 and 90-210, min post-exercise (P < 0.05).

5.6.2 Body temperatures (T_c, T_m and T_sk)

T_c responses during each of the recovery conditions are shown in Figure 5.2. There was a main effect for recovery condition where T_c was higher during HWI than both CWI and CON (P < 0.01), a significant recovery x time interaction (P < 0.01). T_c in the CWI condition was significantly lower than CON from 60-150 min post-exercise, and significantly lower than HWI from 20-210 min post-exercise (P < 0.05). T_c in the HWI condition was significantly higher than CON from 25-150 min post-exercise (P < 0.05). T_c increased from baseline to the
end of exercise and to 5 min post-exercise in all conditions (Figure 5.2) (P < 0.05). There were no differences in Tc between body composition groups at any time-point during any trial (P > 0.05). The lowest post-CWI Tc (LM-LF 36.09 ± 0.38, HM-LF 36.44 ± 0.61, HM-HF 36.53 ± 0.37 °C) and time to reach lowest post-CWI Tc (LM-LF 1:06:40 ± 0:27:29, HM-LF 1:23:20 ± 0:23:20, HM-HF 1:33:20 ± 0:33:54 h:mm:ss) were not significantly different (P > 0.05) between body composition groups.

There was a recovery condition effect for Tm (Figure 3) where muscle temperature was significantly different between CWI, HWI and CON (P ≤ 0.01). There were also significant body composition x time (P = 0.02), recovery x time (P = 0.0001) and recovery x time x body composition group (P= 0.01) interactions. Mean Tm was significantly lower in the CWI condition compared to both the CON and HWI conditions from 20-270 min post-exercise (P < 0.05). Additionally, mean Tm was significantly higher in the HWI condition compared to the CON condition from 20-35 min post-exercise (P < 0.05). Mean Tm at 5 min post-exercise was not different between body composition groups during the CON and HWI trials (P > 0.05) (Figure 5.3). During CWI, Tm was lower in LM-LF compared to HM-HF (5-15 min), and in HM-LF (P = 0.04, 0.05, 0.04 respectively) compared to HM-HF (5 min) (P = 0.04). Post-immersion mean Tm remained lower in the HM-LF group compared with the HM-HF group from 120-270 min post-exercise (P < 0.05).

There was a main effect for recovery condition where Tsk was higher during HWI than both CWI and CON and lower during CWI than both HWI and CON (P < 0.01). There was also a significant recovery x time (P < 0.01) and time x body composition group (P = 0.03) interaction. Mean Tsk was significantly lower in the CWI condition compared to both the CON and HWI conditions from 20-180 min post-exercise (P < 0.05). Mean Tsk was significantly higher in the HWI condition compared to CON from 20-30 min post-exercise (P < 0.05). Mean Tsk was not different from baseline at any time-point during CON. During the CWI trial mean Tsk was lower than baseline from 5 min of immersion until 150 min post-exercise (P < 0.05). During the HWI trial mean Tsk was significantly elevated from 5 min post-exercise until 15 min of recovery (P < 0.05). Mean Tsk was not different between body composition groups at any time-point in each recovery condition.
Figure 5.2: Core Temperature (Mean ± SD) responses of different body composition groups in response to cold water immersion (CWI), hot water immersion (HWI) and control (CON).

○ LM-LF = low mass and low fat, ▲ HM-LF = high mass and low fat, ■ HM-HF = high mass and high fat. Rec = Recovery intervention. † Significantly different from baseline (p < 0.05).
Figure 5.3: Vastus lateralis intramuscular temperature (mean of three measurement depths ± SD) responses of different body composition groups in response to cold water immersion (CWI), hot water immersion (HWI) and control (CON). ○ LM-LF = low mass and low fat, ▲ HM-LF = high mass and low fat, ■ HM-HF = high mass and high fat. Rec = Recovery intervention. * Significant difference between HM-HF & LM-LF (p < 0.05), # Significant difference between HM-LF & HM-HF (p < 0.05).
There was a main effect for recovery condition for $T_c$ after-drop, peak-drop and recovery-drop ($P < 0.01$); however, there were no differences in $T_c$ after-drop, peak-drop or recovery-drop between body composition groups in any recovery condition (Table 5.2). The rate of after-drop (after-drop/time to reach lowest $T_c$) during CWI (LM-LF 0.03 ± 0.01, HM-LF 0.02 ± 0.01 and HM-HF 0.01 ± 0.001 °C/min) was significantly faster in the LM-LF group compared with HM-HF ($P = 0.002$). There was a main effect for recovery condition $T_m$ after-drop, peak-drop and recovery-drop ($P < 0.01$) and a recovery x body composition group interaction for $T_m$ peak-drop and recovery-drop ($P < 0.05$). $T_m$ after-drop was greater during HWI than both CWI and CON and lower during CWI than both HWI and CON ($P < 0.01$). There were no differences between body composition groups for $T_m$ after-drop in any recovery condition or peak-drop and recovery drop in the CON and HWI conditions (Table 2). In the CWI condition, $T_m$ recovery-drop was significantly greater in the LM-LF compared to the HM-LF group ($P = 0.028$) and significantly greater in the HM-LF compared to the HM-HF group ($P = 0.036$). Additionally, $T_m$ peak-drop was significantly greater in the LM-LF compared to the HM-LF group ($P = 0.032$) and significantly greater in the HM-LF compared to the LM-LF and HM-HF groups ($P = 0.037$) in the CWI condition.
Table 5.2: Core and muscle temperature after-drop, peak-drop and recovery-drop.

<table>
<thead>
<tr>
<th></th>
<th>Core Temperature</th>
<th>Muscle Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CON</td>
<td>CWI</td>
</tr>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>After-drop (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM-LF</td>
<td>-1.02 ± 0.19</td>
<td>-1.58 ± 0.27</td>
</tr>
<tr>
<td>HM-LF</td>
<td>-1.00 ± 0.26</td>
<td>-1.26 ± 0.45</td>
</tr>
<tr>
<td>HM-HF</td>
<td>-0.86 ± 0.34</td>
<td>-1.23 ± 0.38</td>
</tr>
<tr>
<td>Peak-drop (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM-LF</td>
<td>-1.58 ± 0.32</td>
<td>-2.41 ± 0.38</td>
</tr>
<tr>
<td>HM-LF</td>
<td>-1.72 ± 0.26</td>
<td>-2.06 ± 0.61</td>
</tr>
<tr>
<td>HM-HF</td>
<td>-1.67 ± 0.22</td>
<td>-1.97 ± 0.37</td>
</tr>
<tr>
<td>Recovery-drop (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM-LF</td>
<td>-0.56 ± 0.29</td>
<td>-0.88 ± 0.21</td>
</tr>
<tr>
<td>HM-LF</td>
<td>-0.72 ± 0.20</td>
<td>-0.80 ± 0.23</td>
</tr>
<tr>
<td>HM-HF</td>
<td>-0.79 ± 0.36</td>
<td>-0.75 ± 0.40</td>
</tr>
</tbody>
</table>

LM-LF = low mass, low fat group, HM-LF = high mass, low fat group, HM-HF = high mass, high fat group. * Significant difference between LM-LF & HM-HF (p < 0.05). # Significant difference between HM-LF & HM-HF (p < 0.05).
Large significant correlations were observed between $T_c$ after-drop and BMI and BSA:M and moderate correlations were observed between $T_c$ after-drop and percent body fat, body mass, fat mass and sum of seven skinfolds in the CWI condition (Figure 5.4A). There was a moderate relationship between lean mass and $T_c$ after-drop in the CON condition and no significant relationships in the HWI condition (Figure 5.4A). No significant relationships were observed between any body composition variable and $T_c$ peak-drop or recovery-drop in any recovery condition. Moderate correlations between $T_m$ peak-drop and fat mass, BMI, sum of seven skinfolds, thigh skinfold, leg fat mass and BSA:M were observed in CWI, and with sum of seven skinfolds in CON. There were no correlations between body composition and mean $T_m$ peak-drop in the HWI condition. There were no correlations mean $T_m$ after-drop or recovery-drop and body composition in any recovery condition.
Figure 5.4: Correlation between body composition variables and A) core temperature after-drop, B) mean muscle temperature peak-drop (Mean ± 90 % CI). ○ CWI ■ CON ▲ HWI. %BF- Body fat percentage, BMI- Body mass index, LM- Lean mass, FM- Fat mass, Sum7-sum of seven skinfolds, BSA-body surface area, Mass- body mass, BSA:M- body surface area to mass ratio, Th sk- mid-thigh skinfold, Leg FM- left leg fat mass. CON = control, CWI = cold water immersion, HWI = hot water immersion. Dotted line = moderate correlation, dashed line = strong correlation. * Significant correlation p ≤ 0.05.
5.6.4 Thermal sensation

There was a main effect for recovery condition where thermal sensation was higher during HWI than both CWI and CON (P = 0.0001). There was also a significant main effect for time (P = 0.0001) and a recovery x time interaction (P = 0.0001). Ratings of thermal sensation were significantly different between CON and CWI from 20-150 min post-exercise, between CON and HWI from 20-35 min post-exercise and between CWI and HWI from 20-150 min post-exercise (P < 0.05). Ratings of thermal sensation increased significantly (P < 0.05) following exercise in all groups. In the CWI trial, thermal sensation was significantly lower (P < 0.05) than baseline from 15 min of recovery until the end of the trial in all groups. Thermal sensation was not different between body composition groups at any time-point in each recovery condition (P = 0.409).

5.6.5 Blood flow and blood pressure

There were significant recovery condition and time effects for both arm and leg blood flow (P < 0.01). Additionally, there were significant recovery x time (P < 0.01) and recovery x time x body composition group (P = 0.04) interactions for leg blood flow. Arm blood flow was significantly lower in the CWI compared to both CON and HWI from 35-270 min post-exercise and in the HWI arm blood flow was significantly higher than CON from 35-60 min post-exercise (P < 0.05). Leg blood flow was significantly lower in CWI compared to CON from 60-270 min post-exercise and significantly lower than HWI from 35-270 min post-exercise (P < 0.05). In the HWI condition leg blood flow was significantly higher than CON from 35-60 min post-exercise. Arm and leg blood flow responses were not different between body composition groups at any time-point in each recovery condition (Figure 5.5). The leg-to-arm blood flow ratio was not different (P ≥ 0.05) between body composition groups at any time-point in any recovery condition (Figure 5.6). When all participants were combined the leg-to-arm blood flow ratio was not different (P ≥ 0.05) between conditions at baseline or 5 min post-exercise. After CWI the ratio increased and was higher than both CON and HWI at 35 and 60 min post-exercise (P ≤ 0.03) and higher than HWI at 90 and 120 min post-exercise (P ≤ 0.05). There were no differences (P ≥ 0.05) in BP between body composition groups at any time-point in any recovery condition. Vascular conductance (limb blood flow/mean arterial pressure) was calculated, however this did not alter the blood flow findings and data are not presented.
Figure 5.5: Arm and leg blood flow (Mean ± SD) responses of different body composition groups in response to cold water immersion (CWI), hot water immersion (HWI) and control (CON). ○ LM-LF = low mass and low fat, ▲ HM-LF = high mass and low fat, and ■ HM-HF = high mass and high fat. Rec = Recovery Intervention. Dashed line = mean baseline value. † Significantly different from baseline (p < 0.05).
5.7 Discussion

The present study aimed to determine the influence of body composition on thermal and limb blood flow responses to post-exercise immersion in cold and hot water, compared with a control condition. The main findings were: 1) CWI caused significant reductions in $T_c$, $T_m$ and limb blood flow whereas there was no significant change in HWI and CON; 2) $T_m$ remained lowest during the post-CWI period in individuals with high mass and low fat compared to those with high mass and high fat and those with low mass and low fat; 3) $T_c$ after-drop and $T_m$ peak-drop in response to post-exercise CWI were correlated with the body surface area to mass ratio and all measures of adiposity; and 4) blood flow responses were not different between body composition groups in any recovery condition.
There were no differences in the $T_c$ responses to HWI and CON between body composition groups. This conflicts with previous observations whereby low fat individuals had significantly higher $T_c$ after 5 min of HWI that was not preceded by exercise. The conflicting findings are likely due to the greater thermal gradient in the pre-exercise state. Participants in the previous study had a $T_c$ of 36.5 °C, compared with a post-exercise $T_c$ of 38.5 °C in the present study, which was closer to the water temperature (38.0 °C) resulting in a lower temperature gradient. With $T_c$ being so close to water temperature during HWI in the present study, the potential for both dry and evaporative heat transfer is minimal which may explain why no differences were observed between groups. This suggests that the current practice of athletes completing HWI soon after exercise will not likely result in additional thermal strain above what is induced by exercise. It will however, delay the return to thermal homeostasis. Nevertheless, further research examining the impact of different HWI protocols, particularly with hotter water temperatures and/or longer immersion durations is warranted to examine the effect of post-exercise HWI, which further elevates thermal strain and the associated thermal and physiological responses of athletes.

The decline in $T_c$ during CWI is inversely related to adipose tissue, and the present study found significant correlations between measures of adiposity (fat mass, sum of seven skinfolds and percent body fat) and $T_c$ after-drop (Figure 5.4A). $T_c$ after-drop is defined as the continued drop in $T_c$ during the initial period after the cold stimulus is removed and is hypothesized to result from conductive transfer after cool blood is circulated during re-warming. Participants were monitored during re-warming for 240 min post-immersion to examine the time-course of temperature change, revealing that time of peak after-drop for individuals ranged from 30 to 150 min post-immersion. One factor potentially impacting the time course of $T_c$ change is the choice to measure $T_c$ via rectal thermometer, as previous research has shown that oesophageal and aural canal temperature respond faster during and post-exercise. Therefore, the time course of $T_c$ change may have differed if a different temperature site was chosen.

Our findings that the LM-LF group have a significantly faster rate of after-drop compared to the HM-HF group concurs with previous observations that low fat males have greater $T_c$ reductions during CWI compared to their higher fat counterparts. We were able to extend this work by incorporating groups differing in both mass and/or body fat. As the $T_c$ response of the HM-LF group did not differ to the other groups, we are unable to conclude whether the lower $T_c$ in the LM-LF group following CWI (Figure 5.2) was influenced by lean mass, fat mass or
both. However, the correlations between adiposity and $T_c$ after-drop following CWI, and the lack of correlation with lean mass across all participants provides some support for the notion that body fat is an important determinant of individual thermal responses.

Body fat was also found to have a significant impact on mean $T_m$ responses to CWI, as reflected by the greater decrements in $T_m$ following CWI in both low-fat groups (LM-LF and HM-LF). Adipose tissue provides insulation to muscle tissue and impacts the magnitude and rate of intramuscular temperature change in response to cold exposure.\(^{35}\) The correlations between measures of adiposity and mean $T_m$ peak-drop (Figure 5.4B) highlights the impact of body fat on heat conductivity and supports the view that higher body fat impedes cooling.\(^{35}\) When examining temperature at a muscular level it is interesting to note that following CWI, $T_m$ did not return to the expected baseline range (35.3-37.5 °C) within the data collection period in all groups; however $T_m$ did return to the baseline range in both the CON and HWI conditions. $T_m$ remained significantly lower (colder) in the HM-LF group compared to both the LM-LF and HM-HF groups during the full post-CWI period (Figure 5.3). This finding is difficult to account for as $T_sk$ and blood flow were similar between body composition groups and $T_c$ was slightly higher during the post-CWI period. It is possible that differences in muscle mass may explain the slower rate of re-warming in the HM-LF group. Indeed, this group had a higher leg muscle mass as determined by DXA (Table 1). Given that the initial drop in muscle temperature was similar between the LM-LF and HM-LF with CWI, this indicates that differences in muscle mass or total mass may explain the slower rate of re-warming in the HM-LF group. This suggests that the amount of muscle tissue present may be an important factor during the re-warming period and those athletes with greater muscle mass will likely require longer to re-warm following a long duration CWI protocol (e.g. 15 min).

This prolonged decrement in $T_m$ following CWI is of practical significance and should be considered when repeat performance is required, particularly if involving maximal efforts. There is an established relationship between $T_m$ and contraction velocity, with maximal muscle power decreasing 3% for every 1 °C decrease in $T_m$.\(^{51}\) Therefore, repeat performance may be impaired if the timeframe is too short prior to subsequent event performance. When prescribing CWI protocols it is crucial to consider the type of exercise to be performed, timeframe available and environment it is performed in.\(^{50}\) For example, performing CWI during a short timeframe between endurance tasks may provide pre-cooling benefits, in both normothermic and warm or hot conditions. However, when performance requires maximal contractions and the
timeframe between repeat performances is short, CWI induced changes in $T_m$ will likely impair muscular performance. The present study also highlights the need to consider individual differences, for example athletes with low body fat are at risk of “overcooling” if utilising the same protocols as athletes with greater amounts of adipose tissue as they will have a reduced barrier to heat exchange. Furthermore, athletes with high muscle mass will likely take longer to re-warm, thus the timeframe between immersion and repeat performance is a critical consideration. Incorporating an active warm-up strategy between immersion and subsequent performance may assist with reducing any loss of muscle function associated with reduced muscle temperatures. It should be noted that reduced tissue temperatures are beneficial for recovery when reducing secondary muscle damage, therefore the prolonged drop in $T_m$ may also be beneficial. However, this would only be the case when repeat performance is not required for a number of hours.

During cold exposure heat exchange is related to the body surface area to mass ratio (BSA:M), which reflects the influences of the area of skin exposed for thermal exchange and the mass available to provide insulation. Previous observations that temperature responses are not different between high- and low-fat males during cold exposure were attributed to the similar BSA:M of the groups. In the present study BSA:M was significantly different between all three groups (Table 5.1). Significant correlations between BSA:M and $T_c$ after-drop (Figure 5.4A) and mean $T_m$ peak-drop (Figure 5.4B) were observed across the cohort where individuals with the greatest BSA:M had the largest drop in temperature. These correlations highlight the importance of BSA:M and the need to better understand its impact on physiological and performance responses to post-exercise CWI.

Blood flow is an important determinant of heat transfer within the body, and alterations in blood flow distribution are believed to contribute to the positive influence of CWI on tissue injury, inflammation, and whole-body performance (e.g. cycling). Post-exercise CWI facilitates a rapid and pronounced reduction in limb blood flow which was confirmed in the present study (Figure 5.5). There was also an apparent redistribution of blood flow, as indicated by the increase in the leg-to-arm blood flow ratio (Figure 5.6), following CWI compared with HWI and control. The magnitude of increase in leg-to-arm blood flow was previously associated with the fall in $T_c$ following CWI. As such we expected the redistribution of blood flow would be greatest in the LM-LF group, which had the greatest fall in both $T_c$ and $T_m$ with CWI, but this was not the case. This is consistent with recent findings where there was no
difference in leg and skin blood flow responses between CWI at water temperatures of 9 °C and 15 °C. This suggests there may be a temperature threshold, below which there is no further alteration in limb blood flow, which may explain why blood flow differences were not observed between body composition groups. In the same study, CWI at 9 °C led to a prolonged reduction in total haemoglobin measured via near infrared spectroscopy, which may indicate that muscle blood flow was reduced to a greater extent. Whether the muscle blood flow response to CWI differs depending upon body mass and composition remains unknown.

Anecdotally it is often reported that leaner athletes experience greater discomfort and cooling during CWI. The present study did not observe any differences in perceptions of thermal sensation between body composition groups, however both $T_c$ and $T_m$ were lower in the low-fat body composition groups. Therefore, the findings of the present study indicate that body composition does impact body temperature change but not necessarily perceptual responses to CWI. A potential limitation impacting the results of the present study is the large range of ages across participants, however as there was no significant difference in age across the three body composition groups ($P \geq 0.80$) this likely had minimal effect on the findings. A further limitation to interpreting the results of this study is the lack of baseline $T_m$ measurements, these were unable to be included as the $T_m$ probe could not be implanted prior to exercise and it the cost (money, time and participant risk) of an extra injection was not feasible.

5.8 Conclusion

In summary, the present study has shown that when CWI recovery is implemented following exercise, individuals with lower body fat experience greater core cooling post-immersion and individuals with greater muscle mass take longer to re-warm at a muscular level. Furthermore, this study provides support to the hypothesis that body surface area, relative to mass, is an important factor which may influence thermal and physiological responses to CWI. This relationship between body composition and temperature changes highlights the need for future research to determine the optimal degree of temperature change to enhance performance recovery, and how to manipulate this for individuals of varying body compositions.
Chapter Six - Influence of body composition on physiological responses to cold water immersion and the recovery of exercise performance.

Chapter six includes the below manuscript which has been accepted for publication.

**Influence of body composition on physiological responses to cold water immersion and the recovery of exercise performance.**

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Impact Factor: 3.042

**Author Contributions**

Student contribution to work: Involved in the conception of the study, collected all data, analysed and interpreted data, was responsible for writing the first draft of the manuscript including preparation of all figures and tables and modified drafts following co-author recommendations.

Conceived and designed the experiment: JS, SH, JM, CA, DC
Performed the experiment: JS, JM
Analysed the data: JS, CA, DC, SH, JM
Wrote/reviewed the paper: JS, CA, SH, JM, DC, GS
6.1 Abstract

6.1.1 Purpose

To explore the influence of body composition on thermal responses to cold water immersion (CWI) and the recovery of exercise performance.

6.1.2 Methods

Male participants were stratified into two groups; low fat (LF; n = 10); or high fat (HF; n = 10). Participants completed a high intensity interval test (HIIT) on a cycle ergometer followed by 15 min recovery intervention (control (CON) or CWI). Core temperature ($T_c$), skin temperature ($T_sk$) and heart rate were recorded continuously. Performance was assessed at baseline, immediately post-HIIT and 40 min post-recovery using a 4 min cycling time trial (TT), countermovement jump (CMJ), and isometric mid-thigh pull (IMTP) tests. Perceptual measures (thermal sensation (TS), total quality of recovery (TQR), soreness and fatigue) were also assessed.

6.1.3 Results

$T_c$ and TS were significantly lower in LF compared to HF from 10 min ($T_c$: LF 36.5 ± 0.5, HF 37.2 ± 0.6°C; TS: LF 2.3 ± 0.5, HF 3.0 ± 0.7 a.u.) to 40 min ($T_c$: LF 36.1 ± 0.6, HF 36.8 ± 0.7°C; TS: LF 2.3 ± 0.6, HF 3.2 ± 0.7 arbitrary units (a.u.)) following CWI ($P < 0.05$). Recovery of TT performance was significantly enhanced following CWI in HF (10.3 ± 6.1%) compared to LF (3.1 ± 5.6%, $P = 0.01$) however, no differences were observed between HF (6.9 ± 5.7%) and LF (5.4 ± 5.2%) with CON. No significant differences were observed between groups for CMJ, IMTP, TQR, soreness or fatigue in both conditions.

6.1.4 Conclusion

Body composition influences the magnitude of $T_c$ change during and following CWI. Additionally, CWI enhanced performance recovery in the HF group only. Therefore, body composition should be considered when planning CWI protocols to avoid overcooling and maximise performance recovery.
6.2 Introduction

Cold water immersion (CWI) is a popular recovery strategy routinely utilised by athletes to hasten the body’s return to its pre-exercise state.\(^3\) Recently, the popularity of CWI in practical settings has led to increased research. Studies to date have focused predominantly on the recovery of performance and have demonstrated mixed results. While a number of studies have reported that CWI enhances performance recovery, others have observed negligible or detrimental effects; stimulating debate over the true efficacy and potential placebo effects of CWI as a recovery strategy. While some variability can be attributed to differences in exercise mode and technical differences in water immersion protocols (e.g. water temperature, duration, depth and mode),\(^{33,45}\) a large degree of variability is thought to be related to nuances and characteristics of the individual.\(^{120}\) Indeed, considerable inter-individual differences in responses to post-exercise CWI have been observed, yet to date, there has been no attempt to understand and account for this variance in the application of post-exercise CWI.

The use of post-exercise CWI is thought to enhance recovery by decreasing tissue temperature and blood flow, which is believed to alleviate hyperthermia, and cardiovascular strain. It has been suggested that thermal and physiological responses to CWI are likely to be impacted by differences in body size and composition.\(^{110,120}\) Indeed, there is an inverse relationship between body fat and the rate of tissue cooling.\(^{35}\) This is likely due to the low conductivity of body fat, which has an insulating effect impeding decrements in core temperature.\(^{96,120}\)

Body surface area to mass ratio (BSA:M) has also been suggested to impact thermal responses to CWI as heat transfer is influenced by the exposed surface area relative to the mass of the athlete. Although differences in BSA:M have been shown to influence thermal and cardiovascular responses to cold exposure, the exact impact of such characteristics on the effectiveness of post-exercise CWI remains unknown. It may be hypothesised that differences in body fat and/or BSA:M will impact the degree of thermal change in response to post-exercise CWI and consequently performance recovery outcomes. For example, repeat performance capacity may be reduced if the CWI protocol is too severe for individuals with low body fat and high BSA:M ratios as it may result in overcooling.

CWI is often applied unilaterally, with the same immersion protocol implemented for all athletes regardless of individual differences in body composition. A greater understanding of the physiological changes underpinning the use of CWI and how these are influenced by body
composition will assist in the development and optimisation of individualised protocols. Therefore, the aim of the present study was to compare the thermal and performance recovery responses to post-exercise CWI between individuals with low and high body fat, and to establish the relationship between the thermal, physiological and performance changes.

6.3 Methods

6.3.1 Participants

Twenty highly trained male cyclists or triathletes volunteered to participate in the present study and were stratified into one of two groups based on previous research: 1) low fat (LF), body fat percentage ≤ 12.0% (n = 10) or high fat (HF), body fat percentage ≥ 18.0% (n = 10) (Table 6.1). Participants were non-smokers, free of illness/injury and required to have minimum cycling peak power output (PPO) at VO_{2max} of 250 Watts (W). This study was approved by the institutional Human Research Ethics Committees and written informed consent was obtained.
Table 6.1: Participant characteristics.

<table>
<thead>
<tr>
<th>Body composition group</th>
<th>Low Fat (≤ 12%)</th>
<th>High Fat (≥ 18%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 10</td>
<td>n = 10</td>
</tr>
<tr>
<td>Age (yrs.)</td>
<td>29.3 ± 7.2</td>
<td>34.9 ± 7.0</td>
</tr>
<tr>
<td>VO$_2$max (L/min)</td>
<td>4.7 ± 0.4</td>
<td>4.6 ± 0.5</td>
</tr>
<tr>
<td>VO$_2$max (ml.kg.min)</td>
<td>65.2 ± 2.9</td>
<td>54.7 ± 3.4</td>
</tr>
<tr>
<td>PPO (W)</td>
<td>341.2 ± 38.5</td>
<td>333.3 ± 38.7</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>183.8 ± 5.6</td>
<td>179.9 ± 9.6</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>72.8 ± 5.7*</td>
<td>84.6 ± 9.1</td>
</tr>
<tr>
<td>Percent body fat (%)</td>
<td>9.5 ± 2.2*</td>
<td>24.5 ± 5.5</td>
</tr>
<tr>
<td>Fat mass (kg)</td>
<td>6.7 ± 1.8*</td>
<td>20.2 ± 5.9</td>
</tr>
<tr>
<td>Lean mass (kg)</td>
<td>63.6 ± 4.8</td>
<td>62.2 ± 6.4</td>
</tr>
<tr>
<td>BMI (cm/kg)</td>
<td>21.5 ± 1.3*</td>
<td>26.1 ± 2.5</td>
</tr>
<tr>
<td>Sum of 7 skinfolds (mm)</td>
<td>41.8 ± 10.6*</td>
<td>97.8 ± 27.6</td>
</tr>
<tr>
<td>BSA (m$^2$)</td>
<td>1.9 ± 0.1*</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>BSA:M (m$^2$/Kg)</td>
<td>0.026 ± 0.001*</td>
<td>0.023 ± 0.001</td>
</tr>
</tbody>
</table>

BMI = body mass index, VO$_2$max = maximal oxygen uptake, PPO = peak power output, BSA = body surface area, BSA:M = body surface area to mass ratio. *Significant difference between body composition groups (p < 0.05).

6.3.2 Study design

Participants attended the laboratory on six occasions, the first three visits were separated by 3-5 days, while visits 4-6 were separated by 7 days (Figure 6.1). The first visit involving body composition assessments including full body DXA (Lunar Prodigy; GE Healthcare, Madison, WI) and three-dimensional body scan (Vitus Smart XXL, Human Solutions; Kaisersalutern) using previously described procedures. The DXA and 3D scanning provides a more direct measurement of body fat percentage and body surface area which is a strength of the current study. The second visit included familiarisation with the high intensity interval test (HIIT) and performance testing protocols; the third visit involved anthropometry assessment, a maximal incremental cycling test for the determination of VO$_2$max/PPO and further familiarisation with performance testing protocols. The maximal incremental cycling test was performed on a cycle
ergometer (Excalibur Sport, Lode, Netherlands), the test commenced at 125 W and increased by 25 W every 3 min until participants reached volitional fatigue.

During the fourth visit participants completed a full familiarisation of the experimental trial without the recovery intervention. On the fifth and sixth visits, participants completed the experimental trials, consisting of either CWI or control (CON) in a randomised, counterbalanced cross-over design. The randomisation process involved all possible recovery combinations being allocated to numbers (1-20) where even numbers completed CWI then CON and odd numbers completed CON then CWI. Upon commencement of the study each participant was randomly allocated a number by drawing an opaque envelope. Participants in the low fat group had numbers from 1-10 and participants in the high fat group had numbers from 11-20 to draw from. This ensured that there would be an even spread of each possible order of recovery interventions across participants. Trials were performed at the same time of day with participants refraining from exercise, caffeine and alcohol consumption for 24 h, and fasting for 1 h prior. Food intake and exercise diaries were used to ensure consistency across trials. Hydration status was assessed upon waking via urine specific gravity and was consistent across trials. All testing was performed in a temperature controlled laboratory (22.3 ± 0.9 °C).

Each trial commenced with a 5 min warm-up on an arm crank ergometer (Excalibur Sport, Lode, Netherlands) followed by cycling (Wattbike Ltd, Nottingham, UK) at 50% PPO for 3 min, and 70% PPO for 2 min. The arm crank ergometry was chosen to aid in warming-up the body without fatiguing the lower limbs prior to jump testing, this was included after pilot testing indicated that the warm-up was not sufficient for the CWI condition. A jump specific warm-up (6 × body weight squats, and 3 × body weight CMJ performed at a self-selected 70% effort) was also completed. Participants then completed baseline measures for countermovement jumps (CMJ) at body weight and with additional load, isometric mid-thigh pull (IMTP) and a 4 min time trial (TT). Following the TT, participants remained on the cycle ergometer, completing a 3 min recovery at 50 W before commencing the fatiguing cycling (HIIT) protocol (Table 2). The HIIT concluded with a 4 min TT, which was used as a measure of post-exercise performance. Participants then completed the post-exercise CMJ and IMTP. This was followed by a recovery period consisting of either: CWI, 15 min seated whole-body immersion (excluding the head) in 15.9 ± 0.2 °C, this was chosen based on current practice; 33,38 or CON, 15 min seated passive rest. Following the recovery intervention participants rested
passively for 40 min before completing the warm-up and post-recovery performance testing in
the same order as at baseline.

Figure 6.1: Schematic representation of the experimental design and trial protocol. DXA =
dual energy x-ray absorptiometry scan, 3D scan = three-dimensional body scan, skinfolds =
sum of seven skinfolds, HIIT = high intensity interval test, CMJ = countermovement jump,
IMTP = isometric mid-thigh pull, VO2 max = maximal oxygen uptake test, TT = time trial,
Famil = familiarisation, CON = control, CWI = cold water immersion.
6.3.3 Fatiguing high intensity interval test (HIIT)

The fatiguing HIIT (Table 6.2) was performed on the air-braked cycle ergometer (Wattbike Ltd, Nottingham, UK). This protocol was based on the previous work of Halson, et al. 52 and was designed to induce fatigue by challenging different facets of cycling fitness. In the present study, the average power output throughout the entire HIIT had a CV of 3.4 ± 2.2 % across experimental trials.

Table 6.2: HIIT protocol

<table>
<thead>
<tr>
<th>Description</th>
<th>Elapsed time (min)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm-up</td>
<td>0-10</td>
<td>4 min Easy (50-65 % PPO)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 min Moderate (65-72.5 % PPO)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 min Threshold (72.5-80 % PPO)</td>
</tr>
<tr>
<td>Set 1 – Short sprints</td>
<td>10-16</td>
<td>3 × 6s max, 114 sec recovery</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sprint 1: 80 % max (level 6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sprint 2: 100 % max (level 6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sprint 3: 100 % max (level 10)</td>
</tr>
<tr>
<td>Recovery 1</td>
<td>16-20</td>
<td>4 min recovery at 50 W</td>
</tr>
<tr>
<td>Set 2 – Long sprints</td>
<td>20-24</td>
<td>4 × (20 s max, 40 s recovery)</td>
</tr>
<tr>
<td>Recovery 2</td>
<td>24-31</td>
<td>7 min recovery at 50 W</td>
</tr>
<tr>
<td>Set 3 – Repeat Sprints</td>
<td>31-37.5</td>
<td>13 x (20 s max, 10 s recovery)</td>
</tr>
<tr>
<td>Recovery 3</td>
<td>37.5-44.5</td>
<td>7 min recovery at 50 W</td>
</tr>
<tr>
<td>Set 4 – Pursuit effort 1</td>
<td>44.5-48.5</td>
<td>4 × (45 s at 250 W, 15 s max)</td>
</tr>
<tr>
<td>Recovery 4</td>
<td>48.5-55.5</td>
<td>7 min recovery at 50 W</td>
</tr>
<tr>
<td>Set 5 – Pursuit effort 2</td>
<td>55.5-59.5</td>
<td>3 × (1 min at 250 W, 20 s max)</td>
</tr>
<tr>
<td>Recovery 5</td>
<td>59.5-66.5</td>
<td>7 min recovery at 50 W</td>
</tr>
<tr>
<td>Passive rest</td>
<td>66.5-67</td>
<td>30 s passive rest</td>
</tr>
<tr>
<td>Set 6 – Time Trial effort</td>
<td>67-71</td>
<td>4 min TT</td>
</tr>
<tr>
<td>Cool down</td>
<td>71-73</td>
<td>2 min recovery at 50 W</td>
</tr>
</tbody>
</table>

PPO = peak power output, Max = maximal voluntary effort, Level = Wattbike air-resistance level, TT = time trial.
6.4 Measures

6.4.1 Performance tests

Performance changes were assessed using a 4 min maximal cycling time trial (TT). Participants were instructed to complete as much work as possible throughout the 4 min period and were blinded to all feedback except time. Total work (kJ), total distance (m) and average power (W) performed in each TT was recorded. Local muscle function, specifically muscle power, was assessed using a body weight (CMJ-BW) and a weighted (CMJ-WT) countermovement jump test consisting of two sets of three maximal CMJ with the average at each time point used for analysis, the weighted condition was included to assess whether the additional load placed on the system was better able to show fatigue. CMJ-BW was performed with a lightweight aluminium bar (0.4 kg), while the CMJ-WT was performed with a load equivalent to 40% of each individual’s body weight using an Olympic weightlifting bar and plate weights. Ground reaction force produced during each CMJ repetition was captured using a 400S force plate (Fitness Technologies, Adelaide, Australia) and Ballistic Measurement System (BMS) software (Innervations, Perth, Australia), from which jump height (cm), peak concentric jump velocity (m/s), and peak concentric force per unit of body weight (N/Kg) were calculated. Finally, muscle strength was assessed using an isometric mid-thigh pull test (IMTP) conducted in a Smith Machine (Plyopower Technologies, Australia) with ground reaction force recorded using the same force plate and BMS. Participants were instructed to pull on an immovable bar as quickly as possible and maintain the effort for 5 s. Participants performed two trials with 2 min of rest separating each trial. IMTP peak force per unit of body weight (N/Kg) was derived. All performance assessments were performed at baseline, post-exercise and 40 min post-recovery.

6.4.2 Physiological measures

Core temperature ($T_c$) was measured using a disposable rectal thermometer (Monatherm, Mallinckrodt, USA). Skin temperature ($T_{sk}$) was measured at four sites (chest, arm, thigh and calf) using iButton (DS1922L, Maxim Integrated Products Inc., USA) temperature sensors and mean $T_{sk}$ was calculated as $T_{sk} = 0.3 \times (T_{chest} + T_{arm}) + 0.2 \times (T_{thigh} + T_{leg})$. Delta values were calculated for $T_c$ peak-drop, after-drop and recovery-drop. $T_c$ peak-drop was calculated as the difference between immediate post-exercise $T_c$ and the lowest post-exercise $T_c$. $T_c$ after-drop was calculated as the difference between $T_c$ at the end of the recovery intervention and the
lowest post-recovery $T_c$. $T_c$ recovery-drop was calculated as the difference between $T_c$ at the end of exercise and the end of the 15 min recovery intervention. Heart rate was logged throughout the testing session with a heart rate monitor (S810i, Polar, Finland).

6.4.3 Perceptual measures

Rating of perceived exertion (RPE) was measured on a scale from six (no exertion at all) to 20 (maximal exertion), and recorded at the end of each TT and the end of each set during the HIIT protocol. Thermal sensation (TS) was measured on a scale of zero (unbearably cold) to eight (unbearably hot). TS was measured at baseline, post-warm up, throughout the HIIT, every 5 min during the recovery intervention, every 10 min during the 40 min passive rest period, and immediately following the post-recovery performance tests. Perceived fatigue was measured on a 10-point scale (0 = nothing at all, 10 = extremely high). Muscle soreness was measured on a 10-point scale (0 = nothing at all, 10 = extremely high), participants were asked to rate their muscle soreness immediately after performing a standardised half squat to ensure they experienced the same sensation on each occasion. Total quality of recovery (TQR) was measured on a scale from six (no recovery) to 20 (maximal recovery). Fatigue, soreness and TQR were measured at baseline, immediately post-exercise, immediately post-recovery, 40 min post-recovery and at the end of the trial.

6.5 Statistics

Baseline characteristics, HIIT performance and $T_c$ recovery-drop, after-drop and peak-drop between groups (LF and HF) were compared using independent samples t-test. Responses over time were compared using a series of discrete two-way repeated measures ANCOVA grouped as recovery condition (CON and CWI) or body composition group (LF and HF) with BSA as the covariate. Where significant main effects or interactions were detected a univariate analysis of variance was performed. Eta-squared ($\eta^2$) and effect size (Cohen $d$) were used to determine the magnitude of the effect for significant outcomes ($\alpha=.05$) in the ANCOVA and t-tests, respectively. Magnitude of the $\eta^2$ and $d$ were interpreted against the following criteria: 0.0-0.2 trivial, 0.2-0.6 small, 0.6-1.2 moderate, 1.2-2.0 large, and > 2.0 very large. Pearson product-moment correlation was used to assess relationships between body composition characteristics and temperature responses, including relationship between changes in core temperature and performance. Correlations ($r$) were interpreted against the following criteria: $r < 0.1$ trivial, 0.1-
0.3 small, 0.3-0.5 moderate, 0.5-0.7 large, 0.7-0.9 very large, and > 0.9 almost certain.\textsuperscript{148} Significance was accepted at P < 0.05 and data are reported as mean ± standard deviation or r ± 90% confidence limits for correlations.

### 6.6 Results

#### 6.6.1 Time trial performance

Total distance (CON: LF 38.4 ± 1.5, HF 37.9 ± 1.5; CWI: LF 37.9 ± 1.5, HF 38.0 ± 1.3 km), total work (CON: LF 615.0 ± 51.4, HF 592.3 ± 52.8; CWI: LF 619.7 ± 56.5, HF 588.0 ± 52.1 kJ) and average power (CON: LF 156.8 ± 11.8, HF 147.9 ± 12.9; CWI: LF 151.0 ± 15.1, HF 147.4 ± 12.0 W) performed during the HIIT were not significantly (P > 0.05) different between body composition groups in each condition.

TT performance was not significantly different between LF and HF at any time point during both recovery conditions (Table 6.3). There was a significant main effect for time on TT work (P = 0.0001). Following HIIT, TT total work was significantly lower than baseline (P = 0.0001, CON $\eta^2 = 0.62$, CWI $\eta^2 = 0.67$) in LF and HF during both conditions. TT total work increased from post-HIIT to post-recovery in both body composition groups for both recovery conditions. The magnitude of this increase was significantly greater in HF compared with LF (P = 0.027, $\eta^2 = 0.24$) in the CWI condition (Figure 6.2B).
Table 6.3: Time trial performance.

<table>
<thead>
<tr>
<th></th>
<th>Low fat (n = 10)</th>
<th></th>
<th>High fat (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Post-HIIT</td>
<td>Post-recovery</td>
</tr>
<tr>
<td>Total work (Kj)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CON</td>
<td>90.9 ± 12.6</td>
<td>83.5 ± 12.1*</td>
<td>87.7 ± 11.1* #</td>
</tr>
<tr>
<td>CWI</td>
<td>90.7 ± 11.1</td>
<td>83.1 ± 11.7*</td>
<td>85.4 ± 10.8*</td>
</tr>
<tr>
<td>Total Distance (km)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CON</td>
<td>3.1 ± 0.2</td>
<td>3.0 ± 0.2*</td>
<td>3.1 ± 0.1*</td>
</tr>
<tr>
<td>CWI</td>
<td>3.1 ± 0.1</td>
<td>3.0 ± 0.2*</td>
<td>3.0 ± 0.1*</td>
</tr>
<tr>
<td>Average Power (W)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CON</td>
<td>379.0 ± 52.6</td>
<td>348.4 ± 50.3*</td>
<td>366.0 ± 47.6* #</td>
</tr>
<tr>
<td>CWI</td>
<td>378.5 ± 46.3</td>
<td>346.5 ± 49.1*</td>
<td>355.9 ± 45.1*</td>
</tr>
</tbody>
</table>

CON = control, CWI = cold water immersion. * Significantly different to baseline (p < 0.05). # Significantly different to post-HIIT (p < 0.05).

Figure 6.2: Percent change in time trial work (mean ± SD) A: from baseline to post-HIIT, B: from post-HIIT to post-recovery. * Significant difference between body composition groups (p < 0.05). BAS = baseline, PEX = post-HIIT, PREC = post-recovery, CON = control, CWI = cold water immersion, LF = low fat, HF = high fat.
6.6.2 Countermovement jump and isometric mid-thigh pull performance

There were no significant differences in most CMJ performance variables between body composition groups across condition and time (Table 6.4). Peak force per unit of body weight for IMTP was not significantly different between body composition groups in either recovery condition at baseline (CON: LF 20.1 ± 2.6, HF 18.3 ± 3.8; CWI: LF 19.8 ± 3.4, HF 18.1 ± 3.1 N/Kg). The change in IMTP peak force from baseline to post-HIIT tended to be positive in LF and negative in HF although not significantly different between groups. There was a trend for the change in IMTP peak force from post-HIIT to post-recovery to be larger in LF (-7%) compared to HF (-2%), however this was not significantly different.
Baseline HR was not different between body composition groups in each condition (CON: LF 68 ± 8, HF 67 ± 8, CWI: LF 68 ± 8, HF 66 ± 12 bpm). HR increased significantly (P < 0.001, CON $\eta^2 = 0.98$, CWI $\eta^2 = 0.95$) post-HIIT (CON: LF 173 ± 13, HF 170 ± 10, CWI: LF 172 ± 11, HF 171 ± 11 bpm) however this was not significantly different between body composition groups in each condition.

### Table 6.4: Countermovement jump performance.

<table>
<thead>
<tr>
<th></th>
<th>Force (N/Kg)</th>
<th>Velocity (m/s)</th>
<th>Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LF (mean ± SD)</td>
<td>HF (mean ± SD)</td>
<td>LF (mean ± SD)</td>
</tr>
<tr>
<td><strong>CON</strong> Body weight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>baseline</td>
<td>20.1 ± 1.5</td>
<td>20.4 ± 1.9</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>post-exercise</td>
<td>20.1 ± 0.8</td>
<td>20.0 ± 1.7</td>
<td>2.3 ± 0.3</td>
</tr>
<tr>
<td>post-recovery</td>
<td>20.0 ± 1.1</td>
<td>19.9 ± 1.1*</td>
<td>2.5 ± 0.3</td>
</tr>
<tr>
<td><strong>Weighted</strong> Body weight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>baseline</td>
<td>17.0 ± 0.8</td>
<td>16.6 ± 1.3</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>post-exercise</td>
<td>17.3 ± 0.6</td>
<td>16.8 ± 1.4</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>post-recovery</td>
<td>17.2 ± 0.7*</td>
<td>16.7 ± 1.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td><strong>CWI</strong> Body weight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>baseline</td>
<td>20.2 ± 1.2</td>
<td>20.0 ± 1.8</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>post-exercise</td>
<td>20.1 ± 1.2</td>
<td>19.8 ± 1.7</td>
<td>2.4 ± 0.2*</td>
</tr>
<tr>
<td>post-recovery</td>
<td>19.1 ± 1.2*#</td>
<td>19.5 ± 2.3</td>
<td>2.3 ± 0.2#</td>
</tr>
<tr>
<td><strong>Weighted</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>baseline</td>
<td>17.1 ± 0.9</td>
<td>16.8 ± 1.5</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>post-exercise</td>
<td>17.2 ± 0.8</td>
<td>16.9 ± 1.5</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>post-recovery</td>
<td>16.5 ± 0.8*#</td>
<td>16.5 ± 1.5*#</td>
<td>1.8 ± 0.1*</td>
</tr>
</tbody>
</table>

LF = low fat, HF = high fat, CON = control, CWI = cold water immersion, * Significantly lower than baseline (p < 0.05). # Significantly lower than post-exercise (P < 0.05)

### 6.6.3 Heart rate

Baseline HR was not different between body composition groups in each condition (CON: LF 68 ± 8, HF 67 ± 8, CWI: LF 68 ± 8, HF 66 ± 12 bpm). HR increased significantly (P < 0.001, CON $\eta^2 = 0.98$, CWI $\eta^2 = 0.95$) post-HIIT (CON: LF 173 ± 13, HF 170 ± 10, CWI: LF 172 ± 11, HF 171 ± 11 bpm) however this was not significantly different between body composition groups in each condition.
6.6.4 Skin and core temperature

A significant reduction in mean $T_{sk}$ during CWI was observed, with $T_{sk}$ reaching its lowest temperature at 15 min of CWI (LF 17.7 ± 0.6, HF 17.4 ± 0.5 °C, $P < 0.001$, $\eta^2 = 0.97$). There were no significant differences ($P = 0.313$) in $T_{sk}$ between body composition groups at any time-point in both recovery conditions (Figure 6.3). BSA had no effect on $T_{sk}$ change accounting for only 6.6 % (CWI) and 9.9 % (CON) of the variation in $T_{sk}$ change over time. $T_{sk}$ peak-drop (LF -9.2 ± 1.4, HF -9.1 ± 0.6 °C) in the CWI condition was not different between body composition groups.

For $T_c$ there were significant main effects for time ($P = 0.0001$) and body composition x time ($P = 0.0001$) A significant increase in $T_c$ from baseline to immediately post-HIIT was observed in both conditions ($P < 0.05$) (Figure 6.3). There were no significant differences in $T_c$ between body composition groups during CON, however $T_c$ was significantly lower during CWI in LF compared to HF from 10-40 min post-recovery ($P < 0.05$). BSA accounted for only 3.2% (CWI) and 5.8% (CON) of the variation in $T_c$ change as compared to group (LF and HF) accounting for 20.3% (CWI) and 1.8% (CON) of the change in $T_c$ over time. Significant differences between body composition groups were observed for lowest post-CWI $T_c$ (LF 36.10 ± 0.61, HF 36.83 ± 0.63 °C, $P = 0.013$, $d = 1.78$), peak-drop (LF -2.15 ± 0.51, HF -1.28 ± 0.77 °C, $P = 0.006$, $d = -1.33$), after-drop (LF -1.03 ± 0.61, HF -0.66 ± 0.10 °C, $P = 0.050$, $d = -0.85$) and the recovery-drop of $T_c$ (LF -1.11 ± 0.30, HF -0.56 ± 0.42 °C, $P = 0.012$, $d = -1.51$).
Figure 6.3: Core temperature and thermal sensation (mean ± SD) responses to control (CON) and cold water immersion (CWI). HIIT = high intensity interval test, Rec = recovery intervention. * Significant difference between LF and HF (P < 0.05).

### 6.6.5 Perceptual measures

TS increased significantly (P < 0.001, CON $\eta^2 = 0.76$, CWI $\eta^2 = 0.88$) following HIIT and then significantly decreased (P < 0.001) from the end of HIIT to the end of recovery for both body composition groups during both conditions (Figure 6.3). During the CON condition, TS returned to baseline after 15 min of recovery. In the CWI trial, TS was significantly lower (P < 0.001) than baseline after 15 min of recovery and remained below baseline until the end of the 40 min passive recovery period. During CWI, TS was significantly lower in LF compared to HF from 10-40 min post-recovery. BSA accounted for only 4.0% (CWI) and 1.7% (CON) of the variation in TS change as compared to group (LF and HF) accounting for 11.0% (CWI) and 6.0% (CON) of the change in TS over time.
There were no significant differences in perceived TQR, soreness or fatigue between LF and HF at any time point in both CON and CWI conditions. There was also no significant difference in rating of perceived exertion (RPE) during the TT between LF and HF at any time point for both the CON and CWI conditions.

6.6.6 Correlations

In response to CWI, large significant (P < 0.05) correlations (Figure 6.4) were observed between T_c peak-drop and body composition variables (percent body fat, fat mass, body mass index, sum of seven skinfolds, body surface area and body surface area to mass ratio). There were no significant correlations with T_c responses during the CON trial.

Figure 6.4: Correlation between body composition variables and core temperature (T_c) peak-drop. r ± 90% confidence limits. ▲ = CON, △ = CWI. %BF = percentage body fat, BMI = body mass index, LM = lean mass, FM = fat mass, Sum7 = sum of 7 skinfolds, BSA = body surface area, BM = body mass, BSA:M = body surface area to mass ratio. CON = control, CWI = cold water immersion. * significant correlation (P < 0.05).

A significant (P < 0.05) correlation between the T_c percent recovery-drop and the percent change in TT work from post-HIIT to post-recovery was observed (Figure 6.5). There were no significant correlations between T_c percent change and CMJ or IMTP percent change, or between T_c peak-drop, T_c after-drop or any performance measure.
Figure 6.5: Correlation between core temperature (T_c) percent recovery-drop and percentage change in time trial total work from post-HIIT until post-recovery. r = 0.52, p = 0.03 ○ = low fat group, ● = high fat group.

6.7 Discussion

The present study aimed to compare the thermal and performance responses to CWI between two groups differing in relative body fat composition. The primary findings of the present study were: 1) individuals with lower body fat responded to CWI with greater decrements in T_c and lower perceived thermal comfort compared to higher fat individuals; 2) the reduction in T_c that occurred following CWI correlated with a reduction in the recovery of TT performance after high intensity exercise; 3) the magnitude of TT performance recovery was impaired in low fat participants following CWI; and 4) CMJ and IMTP performance was not significantly different between body composition groups at any time-point in either condition.

Body fat is known to modulate thermogenic responses to extreme temperatures, and previous research has found body fat to influence the decline in T_c following post-exercise CWI. The present study observed significant correlations between the T_c peak-drop and measures of body fat across all participants (Figure 6.4). When separated into HF and LF groups, T_c was significantly lower in LF from 10 min post-recovery until 40 min post-recovery (Figure 6.3).
Supporting previous findings that low fat individuals have significantly lower T_c 10-30 min following CWI where there was no prior exercise. Together, these two studies demonstrate that regardless of the temperature gradient between body and water, body fat is an effective insulator impeding the decline in T_c.

In addition to measures of body fat, BSA:M may also be an important factor in determining an individual’s response to cooling. Indeed, found no difference in T_c responses between low and high fat males, indicating that the similar BSA:M between the groups may have offset the differences in body fat. In the present study, BSA:M was higher in the LF group (Table 6.1) supporting the theory that a larger BSA:M facilitates heat exchange. Additionally, the present study identified a strong correlation between BSA:M and T_c peak-drop, whereby the greater the BSA:M the greater the decrement in T_c, which is in agreement with our previous research. It should be noted that our covariate analysis indicates that the effects of body fat percentage on T_c are largely independent of any effect of BSA, indicating that both physique characteristics may need to be taken into consideration when optimising individualised CWI protocols. Future research should aim to determine the combined effect of these body composition variables and how they interact to impact temperature and performance in response to post-exercise CWI. This suggested examination of a wider range of body compositions will enable findings to be extrapolated to a wider group of athletes.

Primarily, CWI enhances recovery by reducing T_c and tissue temperatures, which is thought to initiate a chain of events ultimately leading to reductions in thermal and cardiovascular strain, delayed onset muscle soreness and secondary exercise induced muscle damage. Whilst reducing core and tissue temperature has been suggested as the predominant mechanism of CWI leading to enhanced recovery, the magnitude of reduction required for optimally enhancing performance recovery remains unknown. Correlations from the present study suggest that the greater the percentage change in T_c the greater the decrement in performance (Figure 6.5); such that when the reduction in T_c was greater than 2.5%, CWI had either a negligible or detrimental impact on TT performance. This finding is supported by the negative correlation between the change in T_c and the change in performance observed. Together, these studies demonstrate that there is an optimal cooling threshold and when this threshold is exceeded there is either a negligible or negative effect on performance recovery. Previous research has identified post-exercise CWI to be an effective strategy to maintain TT performance. However, in the present study TT performance was only maintained in the HF
group. It is likely that the LF group did not experience a similar maintenance of TT performance due to the greater cooling effect observed following CWI, suggestive of overcooling.

While this hypothesised optimal cooling threshold appears to hold true for TT performance, the same does not appear to apply to all types of exercise performance, in particular shorter duration explosive muscle function. The present study examined a number of aspects of muscle function (CMJ, IMTP) to gain a broader understanding of the effect of CWI on performance. Previous research has shown that CWI is effective for restoring muscle performance in stretch-shortening activities in the days following exercise, but is ineffective for short-term restoration of force generation. The findings of the present study support these observations. The CMJ and IMTP performance measures did however show high variability across participants which is likely related to the subject population. The participants utilised in this study were highly trained cyclists and triathletes which is a strength for TT performance but due to these participants having little to no habituation to the CMJ and IMTP movement tasks it is also a weakness of the study. Future research is required to fully understand the impact of CWI on the recovery of different types of performance.

6.6 Conclusion

The present study highlights the importance of considering differences in body composition (particularly body fat and BSA:M) when prescribing CWI protocols, and reinforces the potential negative impact of overcooling. Furthermore, a relationship between \( T_c \) reduction and the recovery of performance following post-exercise CWI was identified. Future research should also examine how this relationship may change under different performance scenarios (e.g. endurance vs sprint), environmental conditions (e.g. heat vs cold) and time frames (e.g. minutes vs hours post-immersion). CWI is a useful recovery strategy to enhance thermal, perceptual and performance outcomes when prescribed correctly, however protocols that consider individual differences in body composition may provide the greatest benefit to post-exercise recovery and subsequent performance.
Chapter Seven – General Discussion

7.1 Thesis summary

This thesis aimed to understand why current research shows inconsistencies in performance recovery outcomes following water immersion by specifically investigating and defining the physiological responses to cold water immersion (CWI), examining the impact of variation in CWI protocols and understanding the implications of individual differences in body size and composition. Ultimately this thesis aimed to provide information to assist in optimising and individualising the prescription of CWI protocols for athletes. Three studies were completed in order to address these broad aims. Study One (Chapter Four) examined the impact of variation in protocol factors (water temperature, duration, depth and mode of immersion). From this study, an understanding of how each protocol factor impacts core temperature ($T_c$) change was developed. Study Two (Chapter Five) examined the impact of variation in body size and composition on thermal and blood flow responses to post-exercise CWI. From this research body fat and body surface area to mass ratio were found to have the strongest relationship with $T_c$ change. Study Three (Chapter Six) extended findings from Study Two and examined the impact of body fat by comparing $T_c$ and performance change in response to post-exercise CWI. This study found a relationship existed between $T_c$ change and recovery of performance, where it was possible to negatively impact performance recovery if $T_c$ is decreased too drastically.

The major findings of this thesis expand the current knowledge base for four key areas of CWI research; 1) impact of CWI protocol variability, 2) impact of individual differences, 3) physiological responses to CWI and 4) individualising of CWI protocol prescription.
7.2 Protocol variability

Current CWI protocols utilised both in research and practice vary in terms of the duration, water temperature, depth and mode of immersion and there is a lack of understanding regarding the optimal combination of these factors. Previous research has suggested that the effectiveness of CWI is related to differences in the protocol and that future research should examine a wider range of temperatures, durations and depths across the two modes (continuous vs intermittent) to determine whether a dose-response relationship exists. The impact of variation in each protocol factor must first be examined before prescription of individualised protocols can take place. To further examine the impact of protocol variability Study One (Chapter Four) modelled $T_c$ responses to different CWI protocols and examined the time-course of the change. No previous research has examined the full-time course of responses to CWI or the interaction between each CWI protocol factor. Study One found that immersion mode, temperature and duration all had a significant impact upon immediate post-immersion $T_c$ responses. However, immersion depth did not have a significant impact, these finding have added to the knowledge gap on how individual protocol factors impact $T_c$ responses. Additionally, Study One found the time delay between end of exercise and start of immersion had an impact upon $T_c$ changes post-immersion, whereby the longer the time between exercise ceasing and immersion commencing the lower the post-immersion change in $T_c$ will be. This finding is in line with the those of Cook and Beaven who reported that the timing of CWI strongly influences performance recovery outcomes and suggested the sooner CWI could be utilised post-exercise the better the performance outcomes. The findings of Study One are based on data from only 16 out of a possible 336 combinations of protocol factors due to there being no data available on the remaining 320 combinations. The findings of Study One would be strengthened by the inclusion of a wider range of CWI protocols into the modelling, however research first needs to be conducted on the remaining 320 CWI protocol combinations.
7.3 Body composition differences

It has long been known that individual differences in body size and composition will significantly impact physiological responses to cold exposure,\textsuperscript{34,93,96} however the impact of these individual characteristics on physiological and performance responses to post-exercise CWI as utilised by athletes to enhance recovery remains under-researched. It is postulated that variation at an individual participant/athlete level may be a reason why overall studies have reported mixed results and in order to optimise temperature and blood flow changes, protocols should be individualised. Studies Two and Three (Chapters Five and Six) aimed to compare the responses of individuals with different body compositions with Study Two focused specifically on how thermal and blood flow responses differ between athletes with different body composition while Study Three focused on how thermal and performance responses vary across athletes with high or low body fat. Both studies found significant correlations between the decrease in $T_c$ and $T_m$ and body composition, specifically measures of adiposity (body fat percent, fat mass, and skinfolds) and body surface area to mass ratio. Large inter-individual differences were observed in responses from both of these studies, further supporting the theory that the variability in individual responses is leading to mixed results being reported.

The importance of examining the effect of CWI at an individual athlete level is supported by a recently published study.\textsuperscript{63} This study showed large variability across individuals with one participant improving weightlifting performance by 1.1-2.9 % and another decreasing by 2.9-4.5 % following CWI.\textsuperscript{63} It was therefore concluded that CWI should be individually assessed and tailored to each athletes own response pattern rather than relying on average group results.\textsuperscript{63} The findings of Study Three further support this contention as it was found that when individual participants had a decrease in $T_c$ of $\geq 2.5$ % the recovery of time trial (TT) performance would either be negligible or negatively impacted by CWI. This finding indicates
that it is possible to overcool individual athletes and negatively impact their performance recovery.

7.4 Physiological responses

The precise mechanisms underpinning the effectiveness of CWI remain unclear, however it is thought that the primary ability of cold temperatures to decrease both tissue temperature and hydrostatic pressure re-directing blood flow leads to reduced muscle damage, exercise induced hyperthermia and cardiovascular strain. The time-course of physiological responses and how individual differences in body composition impact physiological change in response to CWI remain unknown. Findings from this PhD support those of previous research showing that CWI leads to significant reductions in skin temperature ($T_{sk}$), muscle temperature ($T_m$), $T_c$ and limb blood flow (Chapters Four, Five and Six). However, this PhD further enhances this knowledge by examining the full time-course over which CWI impacts body temperature and blood flow changes. Study One (Chapter Four) adds to knowledge of the time course of responses as it specifically examined the effect of CWI protocol on $T_c$ change, by separately examining the change in $T_c$ during and post-immersion. $T_c$ was found to significantly decrease immediately post-CWI but also to continue to decrease whilst the participant is resting post-immersion. The greatest difference in $T_c$ between the control and CWI conditions occurred 60 min post-immersion.

The findings of Study Two (Chapter Five) further enhances the knowledge of the time course of physiological responses to post-exercise CWI. $T_{sk}$, $T_m$, $T_c$ and limb blood flow were examined for four hours’ post-immersion, whereas previous research has only examined up to 30 min post-immersion. Changes in $T_{sk}$ and limb blood flow appeared to be more acutely impacted by CWI and were only significantly reduced for 5 min post-immersion. While $T_m$
continued to decrease for up to 30 min post-immersion, $T_c$ was influenced by CWI for the longest period of time post-immersion. Time taken to reach lowest $T_c$ was varied across participants and ranged from 30 to 150 min post-immersion. These findings are somewhat consistent with previous research which found $T_c$ and $T_m$ (1, 2 and 3 cm) were significantly colder than baseline for up to 30 min post-CWI, however the findings of Study Two further enhance this knowledge by showing that some individuals will still continue to have reductions in body temperature for longer than 30 min post-CWI. Whilst this PhD has identified the full time-course of body temperature change and shown that body composition impacts upon physiological responses to post-exercise CWI, further research is required to determine what the optimal physiological response to CWI is for recovery of performance. Additionally, future research then needs to examine how to best induce this change for athletes of varying body compositions using different CWI protocol combinations.

7.5 Individualising protocol prescription

Prescription of CWI protocols is currently performed on a one-size-fits-all basis where an entire team for example will complete the same protocol regardless of individual differences. Recently it has been suggested that in order to optimise body temperature and blood flow reduction, CWI protocols should be individualised based on body composition factors. It has also been suggested that there is a need to better match CWI protocols to the mechanism of fatigue (e.g. thermoregulatory vs exercise induced muscle damage) in order to improve recovery outcomes. All three studies in this PhD aimed to understand the reasons for variability in findings across current research and to enhance the ability to optimise individual CWI protocol prescription. Study One aimed to understand the influence of the CWI protocol itself whereas Studies Two and Three aimed to understand how individual differences impact
upon variability in physiological and performance recovery. The findings of this PhD have addressed the paucity in knowledge identified in the review of literature, specifically this PhD found that when prescribing a CWI protocol, decreasing the CWI water temperature by 1 °C will decrease the change in $T_c$ by 0.025 °C or increasing the duration of CWI by 1 min will decreases change in $T_c$ by 0.018 °C. This PhD also found that variance in individual BSA:M explains 32.4 % of variance in $T_c$ and if $T_c$ is reduced by $\geq 2.5$ % TT performance recovery will be reduced. However, there is still an insufficient knowledge base on whether or not a dose-response relationship exists with CWI protocol prescription or whether other individual characteristics such as age, gender and race interact with body composition to influence responses which must be addressed in order to provide strong recommendations on how to individualise protocol prescription to optimise performance outcomes.

7.6 Future recommendations summary

The findings of the series of studies conducted in this PhD highlight a number of questions which remain to be addressed by future research. Specifically;

- Future research should examine recovery from different exercise modes (e.g. endurance vs sprint, concentric vs eccentric) and aim to determine the optimal degree of body temperature change for different performance types. Once an understanding of the degree of change necessary has been developed then future research can examine how this is best achieved for individual athletes.

- There is a lack of understanding as to whether a dose-response relationship exists with CWI protocols. It is important that future research examines a wider range of combinations of water temperature, duration, depth and mode.
• Further work on the interaction between dose of CWI and individual body composition differences is required. Specifically, it is important that future research attempts to determine how different doses of CWI will interact with individual body composition characteristics (e.g. body fat, muscle mass or body surface area to mass ratio) to lead to body temperature and performance change.

• This PhD research found that body composition has no effect on limb blood flow responses, however future research is needed to examine whether body composition impacts the distribution of this blood flow within the limb (e.g. skin vs muscle).

• While body composition is an important factor impacting individual responses to post-exercise CWI, there are also a number of other individual characteristics which require further investigation. Characteristics such as age, gender and ethnicity also have the potential to influence responses. Age impacts BSA:M and also the responsiveness of blood flow in masters and youth athletes. Gender differences between males and females, in particular the menstrual cycle impacts basal $T_c$, $T_sk$ and thermosensitivity. Finally, ethnicity impacts upon shivering rate and metabolic rate.

7.7 Conclusions

The results of this thesis highlight that a one-size-fits-all approach to programming post-exercise CWI protocols to enhance performance recovery should not be considered best practice. It was found that the initial interaction between the CWI protocol and the individual characteristics of the athlete will influence the thermal and physiological responses, which subsequently impacts the recovery of performance. Ultimately it can be concluded that CWI is an effective strategy to enhance performance recovery when prescribed correctly. However,
further work is required before specific guidelines on how to individualise protocols can be provided.

7.8 Practical recommendations

Based on the literature reviewed and the findings of the series of studies conducted in this thesis the following practical recommendations can be made.

- The objective of recovery should be established first and where possible the CWI protocol should be specific to the desired outcome. For example, CWI being used to reduce thermal strain will likely be shorter in duration than that required for the reduction of secondary exercise induced muscle damage (e.g. 5-10 min vs 15 min).

- Consideration should be given to the subsequent exercise and the time-frame available between exercise bouts. This PhD found a relationship between $T_c$ reduction and the recovery of performance following post-exercise CWI highlighting that it is possible to overcool athletes and reduce performance if the time between exercise tasks is too short ($\leq 2$ h). A thorough warm-up should be recommended to reduce the risk of overcooling.

- The type of exercise is an important consideration, if for example whole body endurance performance is required CWI may have a positive influence due to pre-cooling effects, however if maximal efforts are required CWI may not be appropriate due to the impact of cold $T_m$ on muscle contractions if performed in a short time frame ($\leq 2$ h) between exercise bouts.

- Body temperature at the beginning of immersion should be considered as athletes commencing the immersion with a high temperature will possess a greater thermal gradient and therefore larger thermal changes are to be expected. Therefore, an athlete with a high $T_c$ may only need a shorter immersion. Practically it is difficult to measure
$T_c$ in the field, however the relationship between thermal sensation and $T_c$ identified in this PhD show that perceptual measures can be used as a surrogate.

- Physique traits should be considered and protocols may need to be individualised based on body fat and muscle mass to ensure optimal cooling. Indeed, this PhD found athletes with the lowest body fat and/or the greatest BSA:M ratio demonstrate a greater fall in $T_c$ and $T_m$ with CWI. Therefore, reduced immersion durations should be applied for athletes with low body fat and or high BSA:M.

- Regional and whole body composition should be assessed by an accepted technique prior to prescribing individual protocols.

- Protocols may need to be altered when considering both youth (adolescent) and master’s athletes compared to adults, as these groups may not tolerate long ($\geq 10$ min) durations of cold water exposure as well as adults.

- Male and female athletes will likely require different protocols, due largely to differences in body composition. Female athletes tend to have a larger BSA:M which may result in greater reductions in $T_c$, meaning that they will likely require shorter duration immersion than males.
References


Appendices

1. Chapter 2 – IJSPP Manuscript
2. Chapter 2 – YLM infographic
3. Chapter 5 – JSS Manuscript
4. Chapter 6 – IJSPP Manuscript
5. Chapter 4 – IJSPP Manuscript
Cold-Water Immersion for Athletic Recovery: One Size Does Not Fit All

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The use of cold-water immersion (CWI) for postexercise recovery has become increasingly prevalent in recent years, but there is a dearth of strong scientific evidence to support the optimization of protocols for performance benefits. While the increase in practice and popularity of CWI has led to multiple studies and reviews in the area of water immersion, the research has predominantly focused on performance outcomes associated with postexercise CWI. Studies to date have generally shown positive results with enhanced recovery of performance. However, there are a small number of studies that have shown CWI to have either no effect or a detrimental effect on the recovery of performance. The rationale for such contradictory responses has received little attention but may be related to nuances associated with individuals that may need to be accounted for in optimizing prescription of protocols. To recommend optimal protocols to enhance athletic recovery, research must provide a greater understanding of the physiology underpinning performance change and the factors that may contribute to the varied responses currently observed. This review focuses specifically on why some of the current literature may show variability and disparity in the effectiveness of CWI for recovery of athletic performance by examining the body temperature and cardiovascular responses underpinning CWI and how they are related to performance benefits. This review also examines how individual characteristics (such as physique traits), differences in water-immersion protocol (depth, duration, temperature), and exercise type (endurance vs maximal) interact with these mechanisms.

**Keywords:** hydrotherapy, body composition, performance, physiology

Recovery interventions have become an integral part of most athletes’ training programs. Adequate recovery enables physiological and psychological functioning to be restored, minimizing the effects of fatigue and allowing athletes to train and compete optimally. Many strategies are used to enhance the recovery process, including, but not limited to, active recovery, stretching, massage, sleep, compression, and hydrotherapy. *Hydrotherapy* is the broad term encompassing cold-water immersion (CWI), hot-water immersion, contrast-water therapy, and thermoneutral-water immersion. CWI is a popular recovery strategy, and there is a growing body of evidence supporting its use. Research has indicated that CWI is useful for maintaining repeat performance in hot environments by reducing thermal strain, reducing muscle soreness, and aiding recovery from secondary muscle damage that may occur after repetitive high-intensity exercise and team sports. CWI has also been shown to be beneficial to perceptions of recovery. Conversely, some studies have shown CWI to have no benefit or detrimental effects on performance recovery. This highlights the need to better understand the physiological mechanisms responsible for performance changes, an area that has received limited attention to date.

It is hypothesized that CWI instigates physiological changes via hydrostatic pressure, redistribution of blood flow, and reductions in core and tissue temperatures. There is evidence that CWI reduces thermal strain, swelling, inflammation, limb blood flow, muscle spasm, and pain. However, the exact thermal and cardiovascular responses to postexercise CWI remain to be fully elucidated. The effect of CWI and the ability to understand the underlying physiological mechanism are determined in part by the immersion protocol used. Optimal protocol parameters will likely differ depending on the outcome of interest and the specific recovery needs, which are determined by the specific perturbations caused by prior exercise and also the time frame available before subsequent performance is required. Current CWI protocols vary, and there is a lack of understanding surrounding optimal duration, temperature, immersion depth, and the number and frequency of immersions. CWI interventions with favorable outcomes tend to be performed in water between 10°C and 20°C, for 5 to 15 minutes for a single immersion protocol or 1 to 5 minutes per immersion for multiple immersions. CWI performed to the level of the hips or shoulders has shown more beneficial performance outcomes than limb-only immersion.

Physiological responses to CWI will also depend on individual characteristics of the athletes or participants, for example their physique traits, yet there has been little regard for individual characteristics in the literature. Understanding the impact of hydrotherapy on all types of performance and the reasons that some individuals have positive outcomes while others do not relies on an improved understanding of physiological changes associated with successful performance recovery. A greater understanding of the physiology behind CWI, the recovery needs of different performance types (eg, endurance vs sprint), and the factors affecting them will assist in developing individualized CWI protocols likely to maximize performance benefits. This review examines thermal and cardiovascular responses underpinning performance recovery benefits of CWI and explores how differences in individual characteristics...
and variance in protocols may influence the physiological and performance responses.

**Performance Effects**

The ultimate goal of using CWI is to enhance subsequent performance; however, as already highlighted, research to date has shown significant variability. One factor likely contributing to this variance is the different exercise protocols used. Performance measures used in the current literature vary and can be broadly categorized as whole-body endurance performance or explosive maximal performance (which includes local muscle function and sprint tests). The differing physiological demands of these exercise modalities result in different effects on recovery, due to the associated mechanisms of fatigue, so studies of each exercise type should be considered independently. While the precise mechanisms of fatigue associated with endurance performance remain widely debated, one may postulate that CWI assists recovery through the effects of cold temperature reducing thermoregulatory fatigue. Studies by Vaile et al (CWI duration 15 min, CWI temperature 15°C), Vaile et al (5 min, 10°C, 15°C, and 20°C and 15 min, 20°C), Vaile et al (14 min, 15°C), and Peiffer et al (5 min, 14°C) found that CWI enabled the maintenance of cycling time-trial performance in the heat in a subsequent bout performed 40 to 155 minutes post-CWI and across subsequent days. In contrast, Peiffer et al and Buchheit et al found that CWI (5 min, 14°C and 10°C, respectively) had no significant effect on 1-km cycling time-trial performance in the heat. The variability in results across these studies highlights the fact that CWI may be more effective for longer-duration, endurance-type exercise. The studies that found performance benefits employed a cycling time trial between 5 and 15 minutes, whereas the 1-km time trial used by the studies showing negligible results only took 1 to 2 minutes to complete, akin to a sprint effort. It has been suggested that CWI is ineffective for high-intensity exercise of short durations due to the lack of thermal strain from the initial bout and the enhanced parasympathetic reactivation, which may affect muscle contractions through the effects on oxygen consumption and glucose metabolism.

Muscle function has been shown to be reduced in response to an acute exercise bout involving eccentric, high-intensity, or prolonged-duration exercise. This has led to the investigation of the impact of CWI on the recovery of muscle function using tests such as maximal voluntary isometric contractions (MVIC), jumps, and sprints. While the mechanisms of fatigue associated with such tests differ from endurance performance, there is still a similar spread of mixed results across studies that have tested CWI. MVIC force was found to be significantly greater at 24 hours postexercise with CWI (10 min, 10°C) compared with thermoneutral-water immersion. Similarly, the decrement in MVIC was reduced after postexercise CWI (2 x 5 min, 10°C), and a faster return to baseline was observed than in the control. Conversely, CWI did not assist recovery of MVIC of the knee extensors compared with a placebo thermoneutral-water immersion. Recovery of jump performance after CWI has shown more positive results, indicating that CWI may be more effective for recovery of stretch-shortening-cycle movements rather than isolated concentric movements (e.g., MVIC). This is supported by White et al, who found that CWI (10 min, 10°C) reduced the decrement in drop-jump height and enabled a faster return to baseline compared with control after a running high-intensity interval-training session. In the same study, recovery of squat-jump height after CWI was not significantly different from control at any time point.

Sprint performance has shown a greater tendency toward being negatively influenced by CWI. Although it has been found that CWI (5 x 1 min, 11°C) enabled 20-m-sprint performance to be better maintained, negligible effects have also been shown as CWI (10 min, 10°C and 2 x 5 min, 10–12°C) was found to have no significant effect on recovery of 10- to 20-m-sprinting performance. Sprint-cycling performance has also shown mostly negative results, with reductions in power after CWI observed across multiple studies. Sprint-cycling performance was reassessed between 5 and 35 minutes post-CWI in the aforementioned studies, so it may be possible that the short time frame led to participants’ being required to perform before muscle tissue had rewarmed. With muscle temperature being an important determinant of muscle power and sprint performance, it is likely that the negative results observed are due to the muscle being cold from the CWI when the performance task was undertaken, so careful consideration of the time frame between immersion and sprint performance is required.

Current literature shows significant variability in the effectiveness of CWI on performance recovery. The type of exercise performed is a critical factor contributing to the variation, and it is hypothesized that endurance and stretch-shortening-cycle exercise will be more responsive to CWI than isolated concentric exercises. However, there is still considerable variance in the recovery of endurance and stretch-shortening-cycle performance across current literature. Part of this variability may be related to the time frame used by current research, particularly when maximal explosive performance is required shortly after CWI. Nevertheless, there remains a need to understand the physiological responses to CWI and how these responses are influenced by the characteristics of the exercise stress.

**Thermal and Cardiovascular Responses to CWI**

CWI stimulates a number of thermal and cardiovascular responses that may contribute to the enhancement of performance recovery. Studies to date have focused mainly on body-temperature, cardiac, and hemodynamic responses to CWI at rest and after exercise. While understanding the impact of CWI on basal physiological responses provides some insight into the mechanisms by which CWI may be effective, it is perhaps most important to understand how these physiological responses might differ after exercise. This section examines the effect of CWI performed both at rest and postexercise on body temperature, cardiovascular dynamics, and blood flow.

**Skin Temperature**

Skin is the first site to respond to cold exposure and is responsible for initiating thermoregulatory responses resulting in core temperature (Tc) and muscle temperature (Tm) change. Skin temperature (Tsk) is significantly reduced during and after CWI without prior exercise and postexercise CWI. Immediately after CWI without prior exercise, reductions of 7°C to 14°C have been observed. Similar reductions in Tsk of 6°C to 18°C have been observed after postexercise CWI. The extended post-CWI change in Tsk has only been examined for 30 to 40 minutes post-CWI, and while significant reductions were found at this time point, the full time course of this “after drop” and its impact on performance recovery remains unknown. However, it is likely that a lower Tsk at the commencement of subsequent performance will enable athletes to perform at higher work outputs for longer, as increases in Tsk signal...
the thermoregulatory responses that limit work outputs to prevent the body from reaching a critical $T_c$.\textsuperscript{22}

**Muscle Temperature**

CWI has been shown to reduce $T_m$, but the magnitude of this reduction varies significantly.\textsuperscript{24,34,37,38} There is currently limited evidence, with different $T_m$ measurement and CWI methodologies making it difficult to determine the true impact of CWI on $T_m$. The variability in responses is highlighted when examining studies that have used the same postexercise CWI protocol (5 min, 14°C) but shown vastly different results with a decrease of 2.5°C and a decrease of 0.4°C in $T_m$\textsuperscript{24,37} while both studies used the same $T_m$-measurement protocol (3 cm into the rectus femoris) and the same CWI protocol, differences existed in the amount of time between the end of exercise and the start of CWI (25 min\textsuperscript{37} vs 7.5 min\textsuperscript{24}), which likely contributed to the differences in $T_m$ at the commencement of CWI (37.8°C\textsuperscript{37} vs 37.0°C\textsuperscript{24}). This difference in temperature would potentially have had an impact on the temperature gradient between the water and the muscle, which may contribute in part to the variability between studies. Variability of responses is also evident after longer-duration CWI protocols (10 min, 8°C and 22°C), with decrements of 0.2°C to 4.0°C observed.\textsuperscript{34,38} However, the variability between these studies is likely due to differences in the preimmersion state of the participants, as Mawhinney et al\textsuperscript{39} used a postexercise study design, whereas Gregson et al\textsuperscript{34} performed CWI without prior exercise, which again would likely have affected the thermal gradient.

The time course of post-CWI changes is also variable, with decrements of 1.0°C to 7.9°C observed 15 to 30 minutes post-CWI.\textsuperscript{34,38,39} Given the relationship between $T_m$ and muscle contractile performance,\textsuperscript{32} it is important to further examine the time course and impact of postexercise CWI on $T_m$ to avoid detrimental effects and optimize beneficial performance effects.

**Core Temperature**

$T_c$ is significantly reduced immediately post-CWI performed without prior exercise and postexercise.\textsuperscript{40} The extent and time course of this reduction is varied, and with inconsistencies in study methodologies it is difficult to determine exactly how CWI affects $T_c$ and subsequent performance. When comparing studies matched for protocol, variability in the immediate post-CWI (5 min, 14°C) responses become obvious with changes of −0.4°C,\textsuperscript{4,40,24} and −0.3°C\textsuperscript{37} observed. The small changes in $T_c$ observed during short-duration (5 min) CWI may be related to the initial redistribution of warm blood from the periphery to the core, which enables the preservation of $T_c$. Furthermore, it is likely that such a short exposure to the CWI stimulus does not sufficiently affect tissue temperature and blood flow, so the potential beneficial effects of a 5-minute CWI may be minimal.

However, the varied $T_c$ response has also been shown to persist for up to 90 minutes\textsuperscript{40} post-CWI, with decrements ranging from 0.1°C to 2.3°C at 30 minutes postimmersion regardless of the duration of CWI (5–20 min). $T_c$ has not been examined beyond 90 minutes post-CWI, so the full time course of the change and recovery remains unknown. As with $T_m$, $T_c$ at the commencement of subsequent performance can potentially have a “precooling” effect and enhance the athlete’s heat-storage capacity, therefore enabling more work to be performed before reaching a critical $T_c$.\textsuperscript{41} Future studies should focus on determining the exact degree of change in $T_c$ that leads to an optimal precooling effect for subsequent performance and how to induce this change across individual athletes or participants.

**Cardiovascular Dynamics**

Increases in hydrostatic pressure with water immersion cause venous and lymphatic compression.\textsuperscript{39} Venous return is sensitive to external pressure, and when hydrostatic pressure exceeds venous pressure, blood flow is redirected from peripheral to central areas. This redistribution of blood flow leads to an increased central blood volume of 1.9 ± 0.5 L, which has been shown to increase right atrial pressure and pulmonary arterial pressure.\textsuperscript{42} This stimulates an increase in cardiac contractility and results in an increased stroke volume of up to 110 ± 2.4 mL.\textsuperscript{43} Similar increases in cardiac output of up to 30% are observed during thermoneutral immersion.\textsuperscript{42}

There have been limited studies on the effect of CWI on cardiac dynamics, and our understanding is somewhat guided by investigations of cold exposure. Cold temperatures can activate shivering thermogenesis, which increases venous return via the activation of muscle-pump activity, although this does not always occur.\textsuperscript{44} Cold exposure also increases sympathetic activity, and the resultant peripheral vasoconstriction facilitates redistribution of blood, increasing central blood volume. These vascular changes contribute to increases in stroke volume, cardiac output, total peripheral resistance, and blood pressure.\textsuperscript{32,43,45} Indeed, a significant increase in cardiac output and stroke volume after CWI (15 min, 15°C) performed at rest has been reported.\textsuperscript{45} While these specific cardiac responses have not been assessed in response to postexercise CWI, it is likely any such improvements in cardiac output would enhance oxygen delivery and the recovery of aerobic performance.

**Limb, Skin, and Muscle Blood Flow**

Consistent with the notion that cold exposure induces peripheral vasoconstriction, most studies have observed reductions in limb blood flow during and after CWI. Femoral-artery vascular conductance is reduced by 75% after postexercise CWI and 30% after CWI without prior exercise.\textsuperscript{34} One might conclude that the reduction in vascular conductance, which is reflective of vessel diameter, indicates the occurrence of vasoconstriction after CWI performed postexercise and at rest.\textsuperscript{34,38} Leg blood-flow responses after CWI without prior exercise have shown CWI (20 min, 13°C) to have no acute effect on leg blood flow,\textsuperscript{46} whereas Vaile et al\textsuperscript{3} found significant reductions in blood flow to the arm and leg from 5 to 40 minutes after postexercise CWI (15 min, 15°C). Large increases in the leg-to-arm blood-flow ratio were also reported, which were taken to reflect a greater reduction in skin flow than muscle flow, and these changes were correlated with the magnitude of the fall in $T_c$ with CWI.

To understand the significance of these blood-flow changes it is important to assess blood flow to the skin and muscle. The effect of CWI (10 min, 8°C and 22°C) on skin blood flow has only been examined by 2 previous studies. It was found that regardless of the preimmersion state (rested or postexercise), a significant reduction in cutaneous vascular conductance of the thigh occurs. This significant reduction was shown to persist from 1 minute post-CWI until 30 minutes post-CWI.\textsuperscript{34,38}

There have been no direct assessments of muscle blood flow in response to CWI. Muscle-tissue oxygenation, measured by near-infrared spectroscopy, is dependent on metabolic activity and blood perfusion and was found to be attenuated after postexercise
CWI (15 min, 10°C). This lends some support to the notion that CWI reduces intramuscular metabolism, although the direct effect on muscle perfusion cannot be determined. Reductions in muscle temperature might be expected to reduce blood flow (perfusion), muscle metabolism, inflammation, and edema. Conversely, vasodilation of the skin, as evidenced by a reduction in skin blood flow with CWI, might enhance the distribution of blood toward working muscles during subsequent performance. Further studies including direct investigations of limb, skin, and muscle blood flow in response to CWI are required to better understand the influence of blood-flow changes on performance recovery.

**Summary of Thermal and Cardiovascular Effects**

Both resting and postexercise CWI cause significant thermal and cardiovascular changes to occur. The magnitude and time course of these thermal and cardiovascular changes are varied, making it difficult to determine the true physiological effect of CWI. Much of this variability is likely related to the disparity in immersion protocols, preimmersion state of the athlete or participant, and individual differences. These variable physiological responses to CWI are likely the cause of the variation in performance recovery.

**Water-Immersion Protocols**

Physiological and performance variation depend (in part) on the “dose” of cooling provided by CWI. No “gold standard” currently exists for CWI, and protocols tend to be based on those used practically without strong efficacy or physiological evidence.

**Temperature**

Water is an effective conductor causing heat exchange to occur 25 times faster than air, placing significant thermal stress on the body. Water temperature has an impact on the duration and level of immersion used, as colder temperatures induce a greater initial “cold shock,” increasing discomfort and possibly limiting exposure to CWI. The impact of water temperature was examined by comparing CWI in 8°C and 22°C and unsurprisingly 8°C resulted in a larger decrement in Tc. Water temperatures of 10°C to 15°C appear to be optimal for performance recovery, but these temperatures are not achievable in a practical setting similar thermal responses may be induced by altering immersion duration or depth.

**Duration**

Duration of immersion is likely to affect the cooling induced by CWI, with a longer exposure to the cold stimulus resulting in a greater thermal effect. CWI durations of 10 to 20 minutes have been suggested as optimal for performance recovery, as anything shorter may not cause sufficient tissue-temperature change. However, duration should be explored in conjunction with water temperature, as colder temperatures will induce a greater thermal stress and therefore cause tissue temperature to decrease at a faster rate. The impact of immersion duration is evident after examining responses when participants completed CWI to the midsternum at 14°C for 5, 10, and 20 minutes. Preimmersion Tm was 38.8°C for all trials, and immediate postimmersion decrements of 2.5°C (5 min), 4.0°C (10 min), and 6.0°C (20 min) were observed. Tc showed similar effects for immersion duration, with a preimmersion Tc of 38.8°C for all trials and immediate postimmersion decrements of 0.3°C (5 min), 0.6°C (10 min), and 1.0°C (20 min). This response continued into the postrecovery period, with Tc at 30 minutes postimmersion showing reductions of 1.3°C (5 min), 1.5°C (10 min), and 2.3°C (20 min).

**Depth of Immersion**

The level of immersion affects thermal and physiological responses in 2 ways; first, if more of the body is exposed there will be greater surface area for heat exchange to occur, and second, the deeper the immersion, the greater the impact of hydrostatic pressure. The influence of immersion depth becomes evident when comparing studies that used similar CWI protocols (15 min, 15°C), differing only in immersion depth. Immediately post-CWI, Vaile et al (whole-body immersion) observed a decrement in Tc of 1.3°C, whereas Crampton et al (leg immersion) only observed a decrement of 0.4°C. Less surface area exposed to the cold stimulus may result in smaller Tc changes. A comparison of 2 studies with different CWI protocols (5 min, 14°C; whole-body immersion 25, 5 min, 10°C, legs only) that found the same immediate postimmersion Tc change (0.4°C) show that different protocol combinations can have the same impact. So while 1 study had a greater surface area exposed to the cold stimulus, the other used a lower water temperature, leading both studies to result in the same degree of Tc change.

**Summary of Water-Immersion Protocols**

Water temperature and the duration and depth of immersion all significantly affect the magnitude and rate of cooling in response to CWI. The interaction between these factors is complex, and while it has been shown that different combinations of these factors can result in the same degree of Tc change, it is unknown whether duration, temperature, or depth will have the greatest impact on thermal and cardiovascular responses. It is also unknown what the optimal combination of these factors is, and further research is required to fully understand the impact of temperature, duration, and depth and how they may interact with individual differences in physique.

**Individual Characteristics and Responses to CWI**

While some of the variability in physiological and performance responses to CWI can be explained by methodological differences or variation in water-immersion protocols, there remains some variability in the literature that indicates that individual characteristics may influence CWI responses. Given the known impact of physique traits on thermoregulatory responses to cold exposure, it is important to consider these traits when trying to understand the variance in the effectiveness of CWI.

**Body Mass, Body Surface Area, and Ratio of Surface Area to Mass**

Body surface area (BSA), body mass, and the ratio of BSA to mass (BSA:M) are considered important factors affecting one’s ability to maintain thermal homeostasis. BSA influences individual responses to thermal exposure, as heat exchange via evaporation, convection, and conduction all depend on the available surface area. While body mass affects the rate of heat production and heat storage, a larger BSA should theoretically cause heat exchange to...
be increased. However, while overweight individuals have a greater BSA than lean individuals, their rates of heat loss are lower due to greater body mass.\(^5\) The BSA:M ratio has been proposed to reflect this interaction between body-trait characteristics, where a larger BSA:M facilitates heat loss and a smaller BSA:M facilitates body insulation (heat storage).\(^5\) From thermoregulatory studies we know that the increase in metabolic rate and decrease in T_s during exposure to cold air is significantly greater in those with a higher BSA:M than in those with a lower BSA:M.\(^5\) However, no studies to date have examined the impact of BSA:M on responses to CWI.

**Body Fat**

Body fat is considered one of the most important body-composition factors affecting the effectiveness of CWI, as it influences both heat conductivity and blood flow.\(^5\) Body fat has a low heat conductivity, providing greater insulation and thermal resistance than skin and muscle.\(^5\) This insulating effect is thought to affect the magnitude and rate of T_m change, as well as the rate of rewarming after cold exposure.\(^5\) Gastrocnemius T_m was found to decrease at a slower rate during cooling in participants with high, compared with low, subcutaneous fat and returned toward baseline at a slower rate.\(^5\) In addition, significant differences in the decrease in maximum T_m were observed between groups where the decrement was greatest in those with less body fat.\(^5\) It is interesting to note, however, that the standard deviations of the drop in 1-cm T_m ranged from 4.4°C to 4.6°C. This variance indicates the wide range of individual responses and highlights the fact that there may have been some individuals who responded more favorably than others in each of the body-composition groups. Blood flow is affected by body fat, as individuals with high body fat have been shown to have a lower than average blood volume per unit weight.\(^5\) This reduced blood volume affects conductive heat transfer through the tissues, improving the insulative capacity of individuals with greater body fat.\(^5\) Body fat varies not only from sport to sport but even within sports.\(^5\) This highlights the fact that even in the same team, athletes' body compositions may vary substantially, so individualizing CWI protocols may be warranted.

**Muscle Mass**

Muscle tissue has a significant impact on individual thermoregulatory responses. Indeed, vasoconstricted muscle was found to provide approximately 80% of total body insulation during resting water immersion.\(^5\) The depth of measurement affects T_m change, whereby deeper muscle tissue (eg, 3-cm depth) takes longer to cool and rewarm than superficial muscle sites.\(^5\) This was supported by the finding that T_m at 1 cm decreased by 6°C, whereas T_m at 3 cm only decreased by 1.5°C immediately after postexercise CWI.\(^5\) Muscularity has been shown to affect T_c responses to exercise, particularly in hot environments, with mesomorphic participants having higher T_c and greater risk of hyperthermia.\(^5\) Mesomorphic athletes are likely to present with higher T_c postexercise, and one might conclude that a greater dose of CWI would be necessary to account for the higher temperatures in these individuals. In contrast, it may also be concluded that the higher T_c may create a greater temperature gradient between the body and the water, therefore increasing the cooling rate, which is in line with Newton's law of cooling.\(^5\) While it is well established that muscle mass affects thermal responses to both exercise and CWI, it has not yet been determined whether a greater dose of CWI is required to enhance recovery for mesomorphic individuals.

**Other Factors**

Other individual differences such as age, gender, and ethnicity also have the potential to affect the responses to CWI, and this is largely due to their relationship with body composition. Age affects thermoregulation; this is shown by examining the young and the elderly, as these groups have lower subcutaneous fat and larger BSA:M than adults.\(^4\) The elderly also experience reduced responsiveness of cutaneous blood flow to cold exposure and erratic temperature regulation.\(^2\) Subcutaneous fat and BSA are also reasons for thermoregulatory differences between genders.\(^4\) Compared with men, women tend to have greater total body fat, thicker layers of subcutaneous fat, and a greater BSA:M.\(^6\) A comparison of men and women with the same body-fat percentage found that women cool to a greater extent, confirming the assumption that lower BSA:M ratios of men is favorable for heat retention.\(^6\) Women's thermo-regulatory responses and thermosensitivity are also influenced by the menstrual cycle, where during the luteal phase T_c and T_k are higher than during the follicular phase.\(^4\) Ethnicity also influences factors such as subcutaneous adipose-tissue thickness, height, BSA, and mass. These genetic differences are believed to explain differences in heat conductance between African Americans and Whites.\(^5\) Given the potential impact of these individual factors on responses to CWI, practitioners should give consideration to age, gender, and ethnicity. CWI protocols used for men's and women's teams, for example, may need to differ to provide optimal benefits for each group of athletes.

**Conclusion**

This review demonstrates that a number of factors have the potential to affect an individual’s response to CWI, and failing to recognize these in the individual prescription of CWI therapy may influence the effectiveness of this as a recovery strategy. This review has focused on temperature and cardiovascular responses to CWI, as these are likely to underpin performance changes and are likely to also influence other outcomes including markers of inflammation and muscle damage. Future research must further investigate the physiological responses to CWI to gain an understanding of the optimal degree of change so that appropriate protocols may be determined. It is also important to further examine all factors that contribute to the variance (eg, immersion protocol and individual characteristics). Physique traits such as body fat, muscle mass, and their regional distribution, plus BSA:M, may influence thermal and physiological responses to water immersion. These individual characteristics have been shown to affect thermal responses to temperature extremes,\(^5\) but the impact on responses specifically to CWI remains unknown.\(^5\) Before using CWI for either research or practical applications, one should give careful consideration to the amount of time between CWI and performance, performance variables and familiarity, the water-immersion protocol (ie, temperature, duration, and depth), environmental conditions and the degree of thermal strain the individual is under, and the characteristics of the individual (ie, physique traits, gender, age, and ethnicity). It is vital that these factors be considered, as their potential impact on results observed may give an inappropriate indication of the true efficacy of CWI.
Practical Recommendations

Based on the evidence reviewed, there is no one-size-fits-all protocol for CWI, and the following suggestions can be made for the determination of appropriate CWI protocols.

- The objective of recovery should be established first, and where possible the cooling protocol should be specific to the desired outcome. For example, CWI to reduce thermal strain will likely be shorter duration than for the reduction of secondary exercise-induced muscle damage.
- Consideration should be given to the subsequent exercise and the amount of time available. If whole-body endurance performance is required, CWI may have positive impacts due to precooling effects, but if maximal efforts are required CWI may not be appropriate due to the impact of cold muscle temperature on muscle contractions.
- Body temperature at the beginning of immersion should be considered, as athletes commencing the immersion with high temperatures will have a greater thermal gradient, and therefore larger thermal changes are to be expected.
- Physique traits should be considered, and protocols may need to be individualized based on body fat and muscle mass to ensure optimal cooling.
- Regional and whole-body composition should be assessed by an accepted technique before prescribing individual protocols.
- Protocols may need to be altered when dealing with both young (adolescent) and masters athletes compared with adults, as these groups may not tolerate long durations of cold-water exposure.
- Male and female athletes will likely require different protocols.

References


# Cold Water Immersion for Athletic Recovery

_Cold water immersion is not one size fits all._

### LESS INTENSE
- **Water Temperature**: 20°
- **Protocol Duration**: 5 min
- **Depth**: Limb only
- **To Reduce**: Low Thermal strain, Low Body Fat, Female Gender

### MORE INTENSE
- **Water Temperature**: 10°
- **Protocol Duration**: 15 min
- **Depth**: At hip or shoulders level
- **To Reduce**: DOMS, High Body Fat, High Muscle Mass, Male Gender, Adult Age

Designed by @YLMSportScience
Influence of body composition on physiological responses to post-exercise hydrotherapy

Jessica M. Stephens, Shona L. Halson, Joanna Miller, Gary J. Slater & Christopher D. Askew


To link to this article: https://doi.org/10.1080/02640414.2017.1355062

Published online: 13 Jul 2017.

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Influence of body composition on physiological responses to post-exercise hydrotherapy

Jessica M. Stephens\textsuperscript{a,b}, Shona L. Halson\textsuperscript{b}, Joanna Miller\textsuperscript{a}, Gary J. Slater\textsuperscript{b} and Christopher D. Askew\textsuperscript{b}

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\textbf{ABSTRACT}

This study examined the influence of body composition on temperature and blood flow responses to post-exercise cold water immersion (CWI), hot water immersion (HWI) and control (CON). Twenty-seven male participants were stratified into three groups: 1) low mass and low fat (LM-LF); 2) high mass and low fat (HM-LF); or 3) high mass and high fat (HM-HF). Experimental trials involved a standardised bout of cycling, maintained until core temperature reached 38.5°C. Participants subsequently completed one of three 15-min recovery interventions (CWI, HWI, or CON). Core, skin and muscle temperatures, and limb blood flow were recorded at baseline, post-exercise, and every 30 min following recovery for 240 min. During CON and HWI there were no differences in core or muscle temperature between body composition groups. The rate of fall in core temperature following CWI was greater in the LM-LF (0.03 ± 0.01°C/min) group compared to the HM-HF (0.01 ± 0.001°C/min) group (P = 0.002). Muscle temperature decreased to a greater extent during CWI in the LM-LF and HM-LF groups (8.6 ± 3.0°C) compared with HM-HF (5.1 ± 2.0°C, P < 0.05). Blood flow responses did not differ between groups. Differences in body composition alter the thermal response to post-exercise CWI, which may explain some of the variance in the responses to CWI recovery.

\textbf{KEYWORDS}

Recovery; cold water immersion; hot water immersion; core temperature; muscle temperature; limb blood flow

\textbf{INTRODUCTION}

The use of hydrotherapy, particularly cold water immersion (CWI), has become common practice for athletes in an attempt to enhance recovery from training and competition (Vaile, Halson, & Graham, 2010). While there is growth in the evidence to support such strategies (Vaile et al., 2011), there remains disparity in protocols utilised (Halson, 2011; Leeder, Gissane, Van Someren, Gregson, & Howatson, 2012) and variability in the reported effectiveness of CWI on performance recovery (Stephens, Halson, Miller, Slater, & Askew, 2017). Similarly, hot water immersion (HWI) is widely utilised (Vaile et al., 2010), however there has been limited investigation into its efficacy for performance recovery, and findings to date have been mixed (Versey, Halson, & Dawson, 2013). This variability presents a challenge in the practical application of hydrotherapy, highlighting the need to better understand the physiological mechanisms responsible for performance recovery, and the individual characteristics that impact upon the physiological responses.

Guidelines for post-exercise hydrotherapy have a “one size fits all” approach, as athletes often complete the same protocol regardless of individual characteristics (Minett & Costello, 2015; Stephens et al., 2017). It is important to recognize that individual athletes may have vastly different physiques which are likely to affect the physiological responses to hydrotherapy (Stephens, Argus, & Driller, 2014). Physique traits such as body fat, muscle mass and body surface area all influence the thermal responses during exposure to extreme environments (Stocks, Taylor, Tipton, & Greenleaf, 2004; Zhang, Huizenga, Arens, & Yu, 2001). For example, subcutaneous fat has an inverse relationship with the rate of decline in body temperature during CWI (Keatinge, 1960), and thermal insulation is increased in individuals with a greater volume of muscle tissue (Anderson, 1999; Toner, Sawka, Foley, & Pandolf, 1986).

Our understanding of the impact of body characteristics on thermal responses to water immersion comes largely from experimental investigations where the study conditions have been vastly different to the water immersion protocols used for recovery in sport. For example, CWI protocols are typically conducted in 5–20°C water for 3–20 min and HWI in water ≥36°C for 10-24min (Versey et al., 2013). Whereas previous research that has aimed to examine the effect of body composition on thermal responses to CWI has used different CWI water temperature ranges 17–28°C and much longer immersion durations 90 min to 10 h (Glickman-Weiss, Goss, Robertson, Metz, & Cassinelli, 1991; Glickman-Weiss, Nelson, & Hearon, 1995a; McArdle, Magel, Gergley, Spina, & Toner, 1984; Prisby, Glickman-Weiss, & Caine, 2000; Prisby, Glickman-Weiss, Nelson, & Caine, 1999; Tikuisis, 2003). These studies have also been limited by small participant numbers (n = 2–6) (Glickman-Weiss et al., 1991, 1995a; McArdle et al., 1984; Prisby et al., 2000, 1999; Tikuisis, 2003), and the use of sub-optimal methods that lack sensitivity for determining body temperature (e.g. tympanic temperature) (Stephens et al., 2014), and body composition (e.g. bioelectrical impedance, surface anthropometry) (Glickman-Weiss et al., 1991; McArdle et al., 1984; Prisby et al., 2000, 1999; Stephens et al., 2014; Tikuisis, 2003). Most importantly, the aforementioned studies have been conducted under resting conditions and
have not examined the impact of body composition on thermal and physiological responses in the post-exercise state when thermal load is increased.

The performance recovery benefits of hydrotherapy depend largely on the magnitude of temperature change and associated physiological perturbations (Ihsan, Watson, & Abbiss, 2016; Machado et al., 2016; Vaile et al., 2011). A better understanding of the impact of body composition on these factors will aid in the optimisation of recovery protocols, and reduce the risk of inadvertent “over-cooling” or “over-heating” which pose a potential risk to the performance and health of athletes. Therefore, the purpose of the present study was to compare thermal and physiological responses to both post-exercise CWI and HWI between individual athletes that differ in body mass and composition.

Methods

Participants

105 active males underwent initial body composition assessment by dual energy x-ray absorptiometry (DXA) to determine suitability for inclusion based on the following criteria: male, aged 18–45 y, training a minimum of 5 hrs per week, minimum cycling peak power output at VO\textsubscript{2max} (PPO) of ≥250 Watts, and body composition characteristics that corresponded with one of the group criteria below. 36 males met these criteria, of whom 27 agreed to participate (Table 1) and were stratified into one of the following groups based on normative athlete characteristics (Withers, Craig, Bourdon, & Norton, 1987): 1) low mass and low fat (LM-LF) BMI ≥21.0 kg/m\textsuperscript{2} and body fat percentage ≤13.0% (n = 9); 2) high mass and low fat (HM-LF) BMI ≥25.0 kg/m\textsuperscript{2} and body fat percentage ≤13.0% (n = 9); or 3) high mass and high fat (HM-HF) BMI ≥25.0 kg/m\textsuperscript{2} and body fat percentage ≥18.0% (n = 9). Participants were non-smokers, free of illness/injury and provided written informed consent prior to participation. Female participants were not considered for this study due to the repeat trial design of the study and the potential confounding effects of menstrual cycle phase on core temperature and thermal sensation (Glickman-Weiss, Cheatham, Caine, Blegen, & Marcinkiewicz, 2000). The study was approved by the institutional Human Research Ethics Committees.

Experimental design

Participants attended the laboratory on five occasions. The first visit involved body composition assessments including DXA (Lunar Prodigy; GE Healthcare, Madison, WI) and three dimensional body scan (Vitus Smart XXL, Human Solutions; Kaisersalutern) for the determination of body composition characteristics using previously described procedures (Daniell, Olds, & Tomkinson, 2012; Nana, Slater, Stewart, & Burke, 2015). The second visit included an anthropometry assessment (skinfolds, height and weight) (Stewart, Marfell-Jones, Olds, & De Ridder, 2011), maximal incremental cycling test for the determination of VO\textsubscript{2max} and PPO (Versey, Halson, & Dawson, 2011), and familiarisation with experimental procedures.

Three experimental trials were then performed in a randomised counterbalanced crossover design, separated by a minimum of 7 days (Figure 1). Participants refrained from exercise, caffeine and alcohol consumption for 24 hr, and fasted for 2 hr prior to each trial. Food intake and exercise diaries were used to ensure consistency across the trials. Trials commenced with baseline measures of core (T\textsubscript{c}) and skin (T\textsubscript{sk}) temperature, thermal sensation, heart rate (HR), blood pressure (BP) and limb blood flow followed by a standardised bout of cycling: 5 min warm up at 40% PPO, followed by a work period at 75% PPO, maintained until T\textsubscript{c} reached 38.5°C. Immediately following exercise an intramuscular temperature probe was inserted for measures of muscle temperature (T\textsubscript{m}). Participants then completed either: i) CWI, 15 min at 15°C; ii) HWI, 15 min at 38°C; or iii) control (CON), 15 min non-immersed seated passive rest, commencing exactly 15 min post-exercise. Immersions were performed while seated with water to the level of the neck and protocols were chosen based on current practice (Versey et al., 2013). Post-recovery measures were conducted at 5 min, then every 30 min until 240 min post-recovery. During the 240 min post-recovery period participants passively rested in a supine position with the exception of a 10 min seated meal break and 5 min bathroom breaks every 60 min. Hydration status on the day of testing was checked by analysing upon waking urine specific gravity and was consistent across trials. Standardised fluid and meals (350ml Up & Go Energise, Toast and Jam) were consumed between the 30 and 60 min post-recovery measures. All testing was performed in a temperature controlled laboratory (23.1 ± 1.2°C, 37.6 ± 10.7% RH).

Table 1. Participant characteristics.

<table>
<thead>
<tr>
<th>Body Composition Group</th>
<th>LM-LF (n = 9)</th>
<th>HM-LF (n = 9)</th>
<th>HM-HF (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>31.4 ± 6.5</td>
<td>29.2 ± 9.3</td>
<td>37.0 ± 5.4</td>
</tr>
<tr>
<td>VO\textsubscript{2max} (L/min)</td>
<td>4.5 ± 0.5</td>
<td>4.7 ± 0.5</td>
<td>4.7 ± 0.6</td>
</tr>
<tr>
<td>PPO (W)</td>
<td>314.9 ± 40.3</td>
<td>316.4 ± 42.7</td>
<td>312.1 ± 36.5</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>185.7 ± 8.2</td>
<td>180.7 ± 5.7</td>
<td>179.3 ± 4.7</td>
</tr>
<tr>
<td>Total mass (kg)</td>
<td>71.8 ± 6.2\textsuperscript{*}</td>
<td>85.2 ± 6.0</td>
<td>91.6 ± 12.3</td>
</tr>
<tr>
<td>Percent body fat (%)</td>
<td>9.1 ± 1.9\textsuperscript{*}</td>
<td>11.7 ± 1.4\textsuperscript{#}</td>
<td>24.8 ± 5.2</td>
</tr>
<tr>
<td>Fat mass (kg)</td>
<td>6.4 ± 1.4\textsuperscript{*}</td>
<td>9.6 ± 1.3\textsuperscript{#}</td>
<td>22.3 ± 6.8</td>
</tr>
<tr>
<td>Total lean mass (kg)</td>
<td>63.4 ± 5.8\textsuperscript{*}</td>
<td>72.1 ± 5.6</td>
<td>66.0 ± 7.5</td>
</tr>
<tr>
<td>Left leg lean mass (kg)</td>
<td>10.8 ± 1.2\textsuperscript{*}</td>
<td>12.9 ± 1.1\textsuperscript{#}</td>
<td>11.2 ± 1.5</td>
</tr>
<tr>
<td>Left leg fat mass (kg)</td>
<td>1.17 ± 0.28\textsuperscript{*}</td>
<td>1.82 ± 0.35\textsuperscript{#}</td>
<td>3.50 ± 0.76</td>
</tr>
<tr>
<td>BMI (kg/m\textsuperscript{2})</td>
<td>20.8 ± 0.6\textsuperscript{*}</td>
<td>26.1 ± 0.7\textsuperscript{#}</td>
<td>28.3 ± 1.7</td>
</tr>
<tr>
<td>Sum 7 (mm)</td>
<td>46.8 ± 5.7\textsuperscript{*}</td>
<td>55.5 ± 4.2\textsuperscript{#}</td>
<td>113.5 ± 35.9</td>
</tr>
<tr>
<td>BSA (m\textsuperscript{2})</td>
<td>1.93 ± 0.15</td>
<td>2.03 ± 0.13</td>
<td>2.07 ± 0.17</td>
</tr>
<tr>
<td>BSA/M (m\textsuperscript{2}/kg)</td>
<td>0.027 ± 0.001\textsuperscript{*}</td>
<td>0.024 ± 0.001\textsuperscript{#}</td>
<td>0.023 ± 0.001</td>
</tr>
</tbody>
</table>

LM-LF = low mass and low fat, HM-LF = high mass and low fat, HM-HF = high mass and high fat. VO\textsubscript{2max} = maximal oxygen uptake, PPO = peak power output, BMI = body mass index, Sum 7 = sum of 7 skinfolds, BSA = body surface area, BSA/M = body surface area to mass ratio. * Significant difference between LM-LF & HM-LF, # Significant difference between HM-LF & HM-HF, + Significant difference between LM-LF & HM-LF. (P < 0.05).

Measurements

Body temperatures (core, skin and muscle) and thermal sensation

Core temperature (T\textsubscript{c}) was measured using a disposable rectal thermometer (Monatherm, Mallinckrodt, USA) (Versey et al., 2011). Skin temperature (T\textsubscript{sk}) was measured at four sites (chest, arm, thigh and calf) using iButton (DS1922L, Maxim Integrated Products Inc., USA) temperature sensors (Juliff et al., 2014) and mean T\textsubscript{sk} was calculated as T\textsubscript{sk} = 0.3×(T\textsubscript{chest}+T\textsubscript{arm})+0.2×(T\textsubscript{high}+T\textsubscript{leg}) (Ramanathan, 1964). Muscle temperature (T\textsubscript{m}) was measured in
the vastus lateralis. A flexible teflon multi-sensor temperature probe (T-336, Physitemp Instruments, USA) was inserted 3 cm below subcutaneous fat, verified using B-mode ultrasound (Terason t3000 Ultrasound System, Teratech Corporation, USA). Each probe consisted of three thermocouples positioned at 1, 2, and 3 cm depth. Tm data were wirelessly transmitted (Thermes USB Data Acquisition System, Physitemp Instruments, USA) and logged every 10 s (DASY Lab 10.0.1, Measurement Computing, USA). A mean of all three depths was calculated for each post-exercise time-point.

Tm and Tc responses were described as: recovery-drop, calculated as the difference from the end of exercise to the end of the recovery (immersion) period; peak drop—the largest fall following exercise; and after-drop—the largest fall following the end of the recovery (immersion) period. Perceived thermal sensation was measured on a scale of zero (unbearably cold) to eight (unbearably hot) (Young & Dawson, 1987).

Forearm and calf blood flow, blood pressure and heart rate

Participants lay supine with the right arm and both legs raised on foam blocks above the level of the heart. Mercury-in-rubber strain gauges (Hokanson, USA) were placed around maximal girth of the right calf and on the forearm 5 cm distal to the olecranon process. Blood flow was assessed in triplicate at the arm and then the leg, with 10 s separating each measurement (Vaile et al., 2011). Measures were averaged to provide a single measure of leg and arm blood flow at each time-point, and the leg-to-arm blood flow ratio was calculated as described previously (Vaile et al., 2011). Brachial blood pressure (BP) was measured between arm and leg blood flow measures (Omron BP791IT, Omron Healthcare, USA). Heart rate (HR) was continuously logged throughout the trial (S810i, Polar, Finland).

Statistical analysis

Physiological responses were initially explored using a three-way (body composition group x recovery intervention x time) mixed analysis of variance (ANOVA) to confirm the presence of the expected differences between recovery conditions. Where there were significant main effects or interactions for recovery condition, further mixed two-way (body composition group x time) ANOVA were carried out to address the primary aim of the study and determine the presence of body composition effects during each of the recovery conditions. Temperature after-drop, peak-drop and recovery-drop were assessed using a two-way (body composition group x recovery condition) mixed ANOVA. Participant characteristics and exercise responses were compared between body composition groups using a one-way analysis of variance (ANOVA). Where significant main effects or interactions were detected, post-hoc analysis was performed using Tukey's HSD procedure. Pearson product-moment correlation was used to assess relationships between body composition characteristics and change in core and muscle temperatures. Correlations (r) were interpreted against the following criteria: r < 0.1 trivial, 0.1–0.3 small, 0.3–0.5 moderate, 0.5–0.7 large, 0.7–0.9 very large, and >0.9 almost certain (Hopkins, Marshall, Batterham, & Hanin, 2009). The significance level was P < 0.05 and data are reported as mean ± standard deviation or r ± 90% confidence limits for correlations. Statistical analyses were conducted using SPSS computer software (Version 19.0, SPSS Inc., Illinois, USA).

Results

All participants had similar (P ≥ 0.05) VO2 max/PPO characteristics (Table 1) and exercise duration for Tc to reach 38.5°C was not different between body composition groups or across recovery conditions (CON: LM-LF 29:38 ± 11:31, HM-LF 34:49 ± 07:07, HM-HF 32:17 ± 09:46; CWI: LM-LF 29:33 ± 09:15, HM-LF 33:47 ± 08:28, HM-HF 33:18 ± 07:16; HWI: LM-LF 28:02 ± 09:41, HM-LF 37:18 ± 05:55, HM-HF 35:06 ± 08:13 mm:ss; P > 0.05). There was a significant recovery effect (P < 0.01) and a recovery condition x time interaction (P < 0.01) for HR. HR was not different between groups at any time point throughout CON or CWI trials. During the HWI trial, HR was significantly higher in the HM-LF group than the LM-LF group at 5–10 min of immersion, and 35 min post-exercise. Additionally, HR was lower in the LM-LF group compared to the HM-HF group at 5–10 min of immersion, and at 35 and 90–210, min post-exercise (P < 0.05).
Tc responses during each of the recovery conditions are shown in Figure 2. There was a main effect for recovery condition where Tc was higher during HWI than both CWI and CON (P < 0.01), a significant recovery x time interaction (P < 0.01). Tc in the CWI condition was significantly lower than CON from 60–150 min post-exercise, and significantly lower than HWI from 20–210 min post-exercise (P < 0.05). Tc in the HWI condition was significantly higher than CON from 25–150 min post-exercise (P < 0.05). Tc increased from baseline to the end of exercise and to 5 min post-exercise in all conditions (Figure 2) (P < 0.05). There were no differences in Tc between body composition groups at any time-point during trial. The lowest post-CWI Tc (LM-LF 36.09 ± 0.38, HM-LF 36.44 ± 0.61, HM-HF 36.53 ± 0.37°C) and time to reach lowest post-CWI Tc (LM-LF 1:06:40 ± 0:27:29, HM-LF 1:23:20 ± 0:23:20, HM-HF 1:33:20 ± 0:33:54 h:mm:ss) were not significantly different (P > 0.05) between body composition groups.

There was a recovery condition effect for Tm (Figure 3) where muscle temperature was significantly different between CWI, HWI and CON (P ≤ 0.01). There were also significant body composition x time (P = 0.02), recovery x time (P ≤ 0.01) and recovery x time x body composition group (p = 0.01) interactions. Mean Tm was significantly lower in the CWI condition compared to both the CON and HWI conditions from 20–270 min post-exercise (P < 0.05). Additionally, mean Tm was significantly higher in the HWI condition compared to the CON condition from 20–35 min post-exercise (P < 0.05). Mean Tm at 5 min post-exercise was not different between body composition groups during the CON and HWI trials (Figure 3). During CWI, Tm was lower in LM-LF compared to HM-HF (5–15 min), and in HM-LF compared to HM-HF (5 min) (P < 0.05). Post-immersion mean Tm remained lower in the HM-LF group compared with the HM-HF group from 120–270 min post-exercise (P < 0.05).

There was a main effect for recovery condition for Tsk after-drop, peak-drop and recovery-drop (P < 0.01); however, there were no differences in Tsk after-drop, peak-drop and recovery-drop between body composition groups in any recovery condition (Table 2). The rate of after-drop (after-drop/time to reach lowest Tsk) during CWI (LM-LF 0.03 ± 0.01, HM-LF 0.02 ± 0.01 and HM-HF 0.01 ± 0.01°C/min) was significantly faster in the LM-LF group compared with HM-HF (P = 0.002). There was a main effect for recovery condition Tsk after-drop, peak-drop and recovery-drop (P < 0.01) and a recovery x body composition group interaction for Tsk peak-drop and recovery-drop (P < 0.05). Tsk after-drop was greater during HWI than both CWI and CON (P < 0.01). There were no differences between body composition groups for Tsk after-drop in any recovery condition or peak-drop and recovery drop in the CON and HWI conditions (Table 2). In the CWI condition, Tsk recovery-drop was significantly greater in the LM-LF compared to the HM-LF group (P = 0.028) and significantly greater in the HM-LF compared to the HM-HF group (P = 0.036). Additionally, Tsk peak-drop was significantly greater in the LM-LF compared to the
HM-LF group (P = 0.032) and significantly greater in the HM-LF compared to the LM-LF and HM-HF groups (P = 0.037) in the CWI condition.

Large significant correlations were observed between Tc after-drop and BMI and BSA:M and moderate correlations were observed between Tc after-drop and percent body fat, body mass, fat mass and sum of seven skinfolds in the CWI condition (Figure 4a). There was a moderate relationship between lean mass and Tc after-drop in the CON condition and no significant relationships in the HWI condition (Figure 4).

Discussion

The present study aimed to determine the influence of body composition on thermal and limb blood flow responses to post-exercise immersion in cold and hot water, compared with a control condition. The main findings were: 1) CWI caused significant reductions in Tc, Tm and limb blood flow whereas there was no significant change in HWI and CON; 2) Tm remained lowest during the post-CWI period in individuals with high mass and low fat compared to those with high mass and high fat and those with low mass and low fat; 3) Tc after-drop and Tm peak-drop in response to post-exercise CWI were correlated with the...
body surface area to mass ratio and all measures of adiposity; and 4) blood flow responses were not different between body composition groups in any recovery condition.

There were no differences in the $T_c$ responses to HWI and CON between body composition groups. This conflicts with previous observations whereby low fat individuals had significantly higher $T_c$ after 5 min of HWI that was not preceded by exercise (Stephens et al., 2014). The conflicting findings are likely due to the greater thermal gradient in the pre-exercise state. Participants in the previous study had a $T_c$ of 36.5°C, compared with a post-exercise $T_c$ of 38.5°C in the present study, which was closer to the water temperature (38.0°C) resulting in a lower temperature gradient. With $T_c$ being so close to water temperature during HWI in the present study, the potential for both dry and evaporative heat transfer is minimal which may explain why no differences were observed between groups. This suggests that the current practice of athletes completing HWI soon after exercise will not likely result in additional thermal strain above what is induced by exercise. It will however, delay the return to thermal homeostasis. Nevertheless, further research examining the impact of different HWI protocols, particularly with hotter water temperatures and/or longer immersion durations is warranted to examine the effect of post-exercise HWI, which further elevates thermal strain and the associated thermal and physiological responses of athletes.

The decline in $T_c$ during CWI is inversely related to adipose tissue (Keatinge, 1960), and the present study found significant correlations between measures of adiposity (fat mass, sum of seven skinfolds and percent body fat) and $T_c$ after-drop (Figure 4(a)). $T_c$ after-drop is defined as the continued drop in $T_c$ during the initial period after the cold stimulus is removed and is hypothesized to result from conductive transfer after cool blood is circulated during re-warming (Romet, 1988). Participants were monitored during re-warming for 240 min post-immersion to examine the time-course of temperature change, revealing that time of peak after-drop for individuals ranged from 30 to 150 min post-immersion. One factor potentially impacting the time course of $T_c$ change is the choice to measure $T_c$ via rectal thermometer, as previous research has shown that oesophageal and aural canal temperature respond faster during and post-exercise (Gagnon, Lemire, Jay, & Kenny, 2010). Therefore, the time course of $T_c$ change may have differed if a different temperature site was chosen.

Our findings that the LM-LF group have a significantly faster rate of after-drop compared to the HM-HF group concurs with previous observations that low fat males have greater $T_c$ reductions during CWI compared to their higher fat counterparts (Glickman-Weiss, Nelson, & Hearon, 1995b). We were able to extend this work by incorporating groups differing in both mass and/or body fat. As the $T_c$ response of the HM-LF group did not differ to the other groups, we are unable to conclude whether the lower $T_c$ in the LM-LF group following CWI (Figure 2) was influenced by lean mass, fat mass or both. However, the correlations between adiposity and $T_c$ after-drop following CWI, and the lack of correlation with lean mass across all participants provides some support for the notion that body fat is an important determinant of individual thermal responses.

Body fat was also found to have a significant impact on mean $T_m$ responses to CWI, as reflected by the greater decrements in $T_m$ following CWI in both low-fat groups (LM-LF and HM-LF). Adipose tissue provides insulation to muscle tissue and impacts the magnitude and rate of intramuscular temperature change in response to cold exposure (Myrer, Myrer, Measom, Fellingham, & Evers, 2001). The correlations between measures of adiposity and mean $T_m$ peak-drop (Figure 4(b)) highlights the impact of body fat on heat conductivity and supports the view that higher body fat impedes cooling (Myrer et al., 2001). When examining temperature at a muscular level it is interesting to note that following CWI, $T_m$ did not return to the expected baseline range (35.3–37.5°C) (Gregson et al., 2011; Peiffer, Abbiss, Watson, Nosaka, & Laursen, 2009a, 2010a) within the data collection period in all groups; however $T_m$ did return to the baseline range in both the CON and HWI conditions. $T_m$ remained significantly lower (colder) in the HM-LF group compared to both the LM-LF and HM-HF groups during the full post-CWI period (Figure 3). This finding is difficult to account for as $T_{sk}$ and blood flow were similar between body composition groups and $T_c$ was slightly higher during the post-CWI period. It is possible that differences in muscle mass may explain the slower rate of re-warming in the HM-LF group. Indeed, this group had a higher leg muscle mass as determined by DXA (Table 1). Given that the initial drop in muscle temperature was similar between the LM-LF and HM-LF with CWI, this indicates

<table>
<thead>
<tr>
<th>Table 2. Core and muscle temperature after-drop, peak-drop and recovery-drop.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>After-drop (°C)</strong></td>
</tr>
<tr>
<td>Core Temperature</td>
</tr>
<tr>
<td>CON  mean±SD</td>
</tr>
<tr>
<td>LM-LF −1.02 ± 0.19</td>
</tr>
<tr>
<td>HM-LF −1.00 ± 0.26</td>
</tr>
<tr>
<td>HM-HF −0.86 ± 0.34</td>
</tr>
<tr>
<td><strong>Peak-drop (°C)</strong></td>
</tr>
<tr>
<td>LM-LF −1.58 ± 0.32</td>
</tr>
<tr>
<td>HM-LF −1.72 ± 0.26</td>
</tr>
<tr>
<td>HM-HF −1.67 ± 0.22</td>
</tr>
<tr>
<td><strong>Recovery-drop (°C)</strong></td>
</tr>
<tr>
<td>LM-LF −0.56 ± 0.29</td>
</tr>
<tr>
<td>HM-LF −0.72 ± 0.20</td>
</tr>
<tr>
<td>HM-HF −0.79 ± 0.36</td>
</tr>
</tbody>
</table>

LM-LF = low mass, low fat group, HM-LF = high mass, low fat group, HM-HF = high mass, high fat group. * Significant difference between LM-LF & HM-HF, # Significant difference between HM-LF & HM-HF (P < 0.05).
that differences in muscle mass or total mass may explain the slower rate of re-warming in the HM-LF group. This suggests that the amount of muscle tissue present may be an important factor during the re-warming period and those athletes with greater muscle mass will likely require longer to re-warm following a long duration CWI protocol (e.g. 15 min).

This prolonged decrement in $T_m$ following CWI is of practical significance and should be considered when repeat performance is required, particularly if involving maximal efforts. There is an established relationship between $T_m$ and contraction velocity, with maximal muscle power decreasing 3% for every 1°C decrease in $T_m$ (Bergh & Ekblom, 1979). Therefore, repeat performance may be impaired if the timeframe is too short prior to subsequent event performance. When prescribing CWI protocols it is crucial to consider the type of exercise to be performed, timeframe available and environment it is performed in (Halson, 2011). For example, performing CWI during a short timeframe between endurance tasks may provide pre-cooling benefits, in both normothermic (Crampton, Donne, Warminster, & Egana, 2013) and warm or hot conditions (Vaile et al., 2011). However, when performance requires maximal contractions and the timeframe between repeat performances is short, CWI induced
changes in $T_m$ will likely impair muscular performance. The present study also highlights the need to consider individual differences, for example athletes with low body fat are at risk of "overcooling" if utilising the same protocols as athletes with greater amounts of adipose tissue as they will have a reduced barrier to heat exchange. Furthermore, athletes with high muscle mass will likely take longer to re-warm, thus the timeframe between immersion and repeat performance is a critical consideration. Incorporating an active warm-up strategy between immersion and subsequent performance may assist with reducing any loss of muscle function associated with reduced muscle temperatures.

During cold exposure heat exchange is related to the body surface area to mass ratio (BSA:M) (McArdle et al., 1984), which reflects the influences of the area of skin exposed for thermal exchange and the mass available to provide insulation (Stephens et al., 2014). Previous observations that temperature responses are not different between high- and low-fat males during cold exposure were attributed to the similar BSA:M of the groups (Glickman-Weiss et al., 1991). In the present study BSA:M was significantly different between all three groups (Table 1). Significant correlations between BSA:M and $T_c$ after-drop (Figure 4(a)) and mean $T_m$ peak-drop (Figure 4(b)) were observed across the cohort where individuals with the

![Image](https://example.com/image1.png)

Figure 5. Arm and leg blood flow (Mean±SD) responses of different body composition groups in response to cold water immersion (CWI), hot water immersion (HWI) and control (CON). ○ LM-LF = low mass and low fat, ▲ HM-LF = high mass and low fat, and ■ HM-HF = High mass and high fat. Rec = Recovery Intervention. Dashed line = mean baseline value. † Significantly different from baseline ($P < 0.05$).

![Image](https://example.com/image2.png)

Figure 6. Leg-to-arm blood flow ratio (Mean±SD) of the cohort (n = 27) in response to ▲ cold water immersion (CWI), ■ hot water immersion (HWI) and ○ control (CON). * Significant difference between CON and CWI ($P \leq 0.05$). # Significant difference between CWI and HWI ($P \leq 0.05$).
greatest BSA:M had the largest drop in temperature. These correlations highlight the importance of BSA:M and the need to better understand its impact on physiological and performance responses to post-exercise CWI.

Blood flow is an important determinant of heat transfer within the body (Xu, Castellani, Santee, & Kolka, 2007), and alterations in blood flow distribution are believed to contribute to the positive influence of CWI on tissue injury, inflammation (Ihsan et al., 2016), and whole-body performance (e.g. cycling) (Choo et al., 2016). Post-exercise CWI facilitates a rapid and pronounced reduction in limb blood flow (Choo et al., 2016; Vaile et al., 2011) which was confirmed in the present study (Figure 5). There was also an apparent redistribution of blood flow, as indicated by the increase in the leg-to-arm blood flow ratio (Figure 6), following CWI compared with HWI and control. The magnitude of increase in leg-to-arm blood flow was previously associated with the fall in Tc following CWI (Vaile et al., 2011). As such we expected the redistribution of blood flow would be greatest in the LM-LF group, which had the greatest fall in both Tc and Tm with CWI, but this was not the case. This is consistent with recent findings of Choo et al. (2016) where there was no difference in leg and skin blood flow responses between CWI at water temperatures of 9°C and 15°C. This suggests there may be a temperature threshold, below which there is no further alteration in limb blood flow, which may explain why blood flow differences were not observed between body composition groups. In the same study, CWI at 9°C led to a prolonged reduction in total haemoglobin measured via near infrared spectroscopy, which may indicate that muscle blood flow was reduced to a greater extent (Choo et al., 2016). Whether the muscle blood flow response to CWI differs depending upon body mass and composition remains unknown.

Anecdotally it is often reported that leaner athletes experience greater discomfort and cooling during CWI. The present study did not observe any differences in perceptions of thermal sensation between body composition groups, however both Tc and Tm were lower in the low-fat body composition groups. Therefore, the findings of the present study indicate that body composition does impact body temperature change but not necessarily perceptual responses to CWI. A potential limitation impacting the results of the present study is the large range of ages across participants, however as there was no significant difference in age across the three body composition groups (P ≥ 0.80) this likely had minimal effect on the findings.

Conclusion

In summary, the present study has shown that when CWI recovery is implemented following exercise, individuals with lower body fat experience greater core cooling post-immersion and individuals with greater muscle mass take longer to re-warm at a muscular level. Furthermore, this study provides support to the hypothesis that body surface area, relative to mass, is an important factor which may influence thermal and physiological responses to CWI. This relationship between body composition and temperature changes highlights the need for future research to determine the optimal degree of temperature change to enhance performance recovery, and how to manipulate this for individuals of varying body compositions.

Acknowledgments

The authors would like to thank all the cyclists who participated in this study. We also acknowledge Dr. Nathan Versey and Mr. Graeme Allbon for their assistance with pilot testing and data collection. This investigation was supported by funding from the Australian Institute of Sport High Performance Sports Research Fund (HPSRF) and Higher Degree Research grants from the University of the Sunshine Coast. The authors declare that there are no conflicts of interest with this study.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Australian Institute of Sport [High Performance Sport Research Fund/STEPHN]; University of the Sunshine Coast [Faculty of Health HDR grant/513461;]

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Article in International journal of sports physiology and performance · August 2017
DOI: 10.1123/ijspp.2017-0083

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**Section:** Original Investigation

**Article Title:** Effect of Body Composition on Physiological Responses to Cold Water Immersion and the Recovery of Exercise Performance

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**Journal:** *International Journal of Sports Physiology and Performance*

**Acceptance Date:** July 26, 2017

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**DOI:** [https://doi.org/10.1123/ijspp.2017-0083](https://doi.org/10.1123/ijspp.2017-0083)
Title:
Effect of body composition on physiological responses to cold water immersion and the recovery of exercise performance.

Submission Type: Original Investigation

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Running head: Physique, cold water immersion and recovery

Abstract word count: 245

Text-only word count: 3505

Number of figures and tables: Figures = 5, tables = 4
ABSTRACT

Purpose: To explore the influence of body composition on thermal responses to cold water immersion (CWI) and the recovery of exercise performance. Methods: Male subjects were stratified into two groups; low fat (LF; n=10); or high fat (HF; n=10). Subjects completed a high intensity interval test (HIIT) on a cycle ergometer followed by 15 min recovery intervention (control (CON) or CWI). Core temperature (T_c), skin temperature (T_sk) and heart rate were recorded continuously. Performance was assessed at baseline, immediately post-HIIT and 40 min post-recovery using a 4 min cycling time trial (TT), countermovement jump (CMJ), and isometric mid-thigh pull (IMTP) tests. Perceptual measures (thermal sensation (TS), total quality of recovery (TQR), soreness and fatigue) were also assessed. Results: T_c and TS were significantly lower in LF compared to HF from 10 min (T_c: LF 36.5±0.5, HF 37.2±0.6 C; TS: LF 2.3±0.5, HF 3.0±0.7 arbitrary units (a.u.)) to 40 min (T_c: LF 36.1±0.6, HF 36.8±0.7 C; TS: LF 2.3±0.6, HF 3.2±0.7 a.u.) following CWI (P<0.05). Recovery of TT performance was significantly enhanced following CWI in HF (10.3±6.1%) compared to LF (3.1±5.6%, P=0.01) however, no differences were observed between HF (6.9±5.7%) and LF (5.4±5.2%) with CON. No significant differences were observed between groups for CMJ, IMTP, TQR, soreness or fatigue in both conditions. Conclusion: Body composition influences the magnitude of T_c change during and following CWI. Additionally, CWI enhanced performance recovery in the HF group only. Therefore, body composition should be considered when planning CWI protocols to avoid overcooling and maximise performance recovery.
INTRODUCTION

Cold water immersion (CWI) is a popular recovery strategy routinely utilised by athletes to hasten the body’s return to its pre-exercise state. Recently, the popularity of CWI in practical settings has led to increased research. Studies to date have focused predominantly on the recovery of performance and have demonstrated mixed results. While a number of studies have reported that CWI enhances performance recovery, others have observed negligible or detrimental effects; stimulating debate over the true efficacy and potential placebo effects of CWI as a recovery strategy. While some variability can be attributed to differences in exercise mode and technical differences in water immersion protocols (e.g. water temperature, duration, depth and mode), a large degree of variability is thought to be related to nuances and characteristics of the individual. Indeed, considerable inter-individual differences in responses to post-exercise CWI have been observed, yet to date, there has been no attempt to understand and account for this variance in the application of post-exercise CWI.

The use of post-exercise CWI is thought to enhance recovery by decreasing tissue temperature and blood flow, which is believed to alleviate hyperthermia, exercise induced muscle damage, and cardiovascular strain, as well as improving autonomic nervous system functioning. It has been suggested that thermal and physiological responses to CWI are likely to be impacted by differences in body size and composition. Indeed, there is an inverse relationship between body fat and the rate of tissue cooling. This is likely due to the low conductivity of body fat, which has an insulating effect impeding decrements in core temperature.

Body surface area to mass ratio (BSA:M) has also been suggested to impact thermal responses to CWI as heat transfer is influenced by the exposed surface area relative to the mass of the athlete. Although differences in BSA:M have been shown to influence thermal and
cardiovascular responses to cold exposure,\textsuperscript{13,17} the exact impact of such characteristics on the effectiveness of post-exercise CWI remains unknown. It may be hypothesised that differences in body fat and/or BSA:M will impact the degree of thermal change in response to post-exercise CWI and consequently performance recovery outcomes. For example, repeat performance capacity may be reduced if the CWI protocol is too severe for individuals with low body fat and high BSA:M ratios as it may result in overcooling.

CWI is often applied unilaterally, with the same immersion protocol implemented for all athletes regardless of individual differences in body composition. A greater understanding of the physiological changes underpinning the use of CWI and how these are influenced by body composition will assist in the development and optimisation of individualised protocols. Therefore, the aim of the present study was to compare the thermal and performance recovery responses to post-exercise CWI between individuals with low and high body fat, and to establish the relationship between the thermal, physiological and performance changes.

**METHODS**

**Subjects**

Forty-eight potential participants volunteered to undergo initial DXA screening. Fifteen were excluded due not meeting body composition criteria, two were excluded due to not meeting minimum fitness requirements and eleven dropped out due to availability or injury issues. Twenty highly trained male cyclists or triathletes participated in the present study and were stratified into one of two groups based on previous research:\textsuperscript{18} 1) low fat (LF), body fat percentage ≤12.0% (n=10) or high fat (HF), body fat percentage ≥18.0% (n=10) (Table 1). Subjects were non-smokers, free of illness/injury and required to have a minimum cycling peak power output (PPO) at VO\textsubscript{2max} of 250 Watts (W). Sample size for this study was based on our previous observation that the fall in T\textsubscript{c} was greater in low-fat individuals (-1.22±0.34°C) than
in high-fat individuals (-0.74±0.18°C). A priori power analysis indicated that 10 participants per group would be sufficient to detect this difference at 30-min post exercise with a power of 0.95 and an alpha of 0.05. This study was approved by the institutional Human Research Ethics Committees and written informed consent was obtained.

**Study Design**

Subjects attended the laboratory on six occasions, the first three visits were separated by 3-5 days, while visits 4-6 were separated by 7 days. The first visit involving body composition assessments including full body DXA (Lunar Prodigy; GE Healthcare, Madison, WI) and three dimensional body scan (Vitus Smart XXL, Human Solutions; Kaisersaltaun) using previously described procedures. The DXA and 3D scanning provides a more direct measurement of body fat percentage and body surface area which is a strength of the current study. The second visit included familiarisation with the high intensity interval test (HIIT) and performance testing protocols; the third visit involved anthropometry assessment, a maximal incremental cycling test for the determination of VO$_{2\text{max}}$/PPO and further familiarisation with performance testing protocols. The maximal incremental cycling test was performed on a cycle ergometer (Excalibur Sport, Lode, Netherlands), the test commenced at 125W and increased by 25 W every 3 min until participants reached volitional fatigue.

During the fourth visit subjects completed a full familiarisation of the experimental trial without the recovery intervention. On the fifth and sixth visits, subjects completed the experimental trials, consisting of either CWI or control (CON) in a randomised, counterbalanced cross-over design. Simple randomisation with stratification was used where separate sets of computer-generated randomisation codes were generated for each group (HF, LF) and stored in opaque envelopes until test-order was allocated at the time of study consent. Trials were performed at the same time of day with subjects refraining from exercise, caffeine
and alcohol consumption for 24 hr, and fasting for 1 hr prior. Food intake and exercise diaries were used to ensure consistency across trials. Hydration status was assessed upon waking via urine specific gravity and was consistent across trials. All testing was performed in a temperature controlled laboratory (22.3±0.9°C).

Each trial commenced with a 5 min warm-up on an arm crank ergometer (Excalibur Sport, Lode, Netherlands) followed by cycling (Wattbike Ltd, Nottingham, UK) at 50% PPO for 3 min, and 70% PPO for 2 min. The arm crank ergometry was chosen to aid in warming-up the body without fatiguing the lower limbs prior to jump testing. A jump specific warm-up (6 × body weight squats, and 3 × body weight CMJ performed at a self-selected 70% effort) was also completed. Subjects then completed baseline measures for countermovement jumps (CMJ) at body weight and with additional load, isometric mid-thigh pull (IMTP) and a 4 min time trial (TT). Following the TT, subjects remained on the cycle ergometer, completing a 3 min recovery at 50 W before commencing the fatiguing cycling (HIIT) protocol (Table 2). The HIIT concluded with a 4 min TT, which was used as a measure of post-exercise performance. Subjects then completed the post-exercise CMJ and IMTP. This was followed by a recovery period consisting of either: CWI, 15 min seated whole-body immersion (excluding the head) in 15.9±0.2°C, this was chosen based on current practice8,23; or CON, 15 min seated passive rest. Following the recovery intervention subjects rested passively for 40 min before completing the warm-up and post-recovery performance testing in the same order as at baseline.

**Fatiguing High Intensity Interval Test (HIIT)**

The fatiguing HIIT (Table 2) was performed on the air-braked cycle ergometer. This protocol was based on the previous work of Halson, et al. 24 and was designed to induce fatigue
by challenging different facets of cycling fitness. In the present study the average power output throughout the entire HIIT had a CV of 3.4±2.2% across experimental trials.

**Performance tests**

Performance changes were assessed using a 4 min maximal cycling time trial (TT). Subjects were instructed to complete as much work as possible throughout the 4 min period and were blinded to all feedback except time. Total work (kJ), total distance (m) and average power (W) performed in each TT was recorded. Local muscle function, specifically muscle power, was assessed using a body weight (CMJ-BW) and a weighted (CMJ-WT) countermovement jump test consisting of two sets of three maximal CMJ with the average at each time point used for analysis. CMJ-BW was performed with a lightweight aluminium bar (0.4 kg), while the CMJ-WT was performed with a load equivalent to 40% of each individual’s body weight using an Olympic weightlifting bar and plate weights. Ground reaction force produced during each CMJ repetition was captured using a 400S force plate (Fitness Technologies, Adelaide, Australia) and Ballistic Measurement System (BMS) software (Innervations, Perth, Australia), from which jump height (cm), peak concentric jump velocity (m/s), and peak concentric force per unit of body weight (N/Kg) were calculated. Finally, muscle strength was assessed using an isometric mid-thigh pull test (IMTP) conducted in a Smith Machine (Plyopower Technologies, Australia) with ground reaction force recorded using the same force plate and BMS. Subjects were instructed to pull on an immovable bar as quickly as possible and maintain the effort for 5 s. Subjects performed two trials with 2 min of rest separating each trial. IMTP peak force per unit of body weight (N/Kg) was derived. All performance assessments were performed at baseline, post-exercise and 40 min post-recovery.
Physiological measures

Core temperature ($T_c$) was measured using a disposable rectal thermometer (Monatherm, Mallinckrodt, USA). Skin temperature ($T_{sk}$) was measured at four sites (chest, arm, thigh and calf) using iButton (DS1922L, Maxim Integrated Products Inc., USA) temperature sensors and mean $T_{sk}$ was calculated as $T_{sk}=0.3(T_{chest}+T_{arm})+0.2(T_{thigh}+T_{leg})$. Delta values were calculated for $T_c$ peak-drop, after-drop and recovery-drop. $T_c$ peak-drop was calculated as the difference between immediate post-exercise $T_c$ and the lowest post-exercise $T_c$. $T_c$ after-drop was calculated as the difference between $T_c$ at the end of the recovery intervention and the lowest post-recovery $T_c$. $T_c$ recovery-drop was calculated as the difference between $T_c$ at the end of exercise and the end of the 15 min recovery intervention. Heart rate was logged throughout the testing session with a heart rate monitor (S810i, Polar, Finland).

Perceptual measures

Rating of perceived exertion (RPE) was measured on a scale from six (no exertion at all) to 20 (maximal exertion), and recorded at the end of each TT and the end of each set during the HIIT protocol. Thermal sensation (TS) was measured on a scale of zero (unbearably cold) to eight (unbearably hot). TS was measured at baseline, post-warm up, throughout the HIIT, every 5 min during the recovery intervention, every 10 min during the 40 min passive rest period, and immediately following the post-recovery performance tests. Perceived fatigue was measured on a 10-point scale (0 = nothing at all, 10 = extremely high). Muscle soreness was measured on a 10-point scale (0 = nothing at all, 10 = extremely high), subjects were asked to rate their muscle soreness immediately after performing a standardised half squat to ensure they experienced the same sensation on each occasion. Total quality of recovery (TQR) was measured on a scale from six (no recovery) to 20 (maximal recovery).
TQR were measured at baseline, immediately post-exercise, immediately post-recovery, 40 min post-recovery and at the end of the trial.

**Statistics**

Baseline characteristics, HIIT performance and $T_c$ recovery-drop, after-drop and peak-drop between groups (LF and HF) were compared using independent samples t-test. Responses over time were compared using a series of discrete two-way repeated measures ANCOVA grouped as recovery condition (CON and CWI) or body composition group (LF and HF) with BSA as the covariate. Where significant main effects or interactions were detected a univariate analysis of variance was performed. Eta-squared ($\eta^2$) and effect size (Cohen $d$) were used to determine the magnitude of the effect for significant outcomes ($\alpha=.05$) in the ANCOVA and t-tests, respectively. Magnitude of the $\eta^2$ and $d$ were interpreted against the following criteria: 0.0-0.2 trivial, 0.2-0.6 small, 0.6-1.2 moderate, 1.2-2.0 large, and >2.0 very large.\textsuperscript{29} Pearson product-moment correlation was used to assess relationships between body composition characteristics and temperature responses, including relationship between changes in core temperature and performance. Correlations ($r$) were interpreted against the following criteria: $r<0.1$ trivial, 0.1-0.3 small, 0.3-0.5 moderate, 0.5-0.7 large, 0.7-0.9 very large, and >0.9 almost certain.\textsuperscript{29} Significance was accepted at $P<0.05$ and data are reported as mean±standard deviation or $r±90\%$ confidence limits for correlations.

**RESULTS**

Total distance (CON: LF 38.4±1.5, HF 37.9±1.5; CWI: LF 37.9±1.5, HF 38.0±1.3 km), total work (CON: LF 615.0±51.4, HF 592.3±52.8; CWI: LF 619.7±56.5, HF 588.0±52.1 kJ) and average power (CON: LF 156.8±11.8, HF 147.9±12.9; CWI: LF 151.0±15.1, HF 147.4±12.0 W) performed during the HIIT were not significantly ($P>0.05$) different between body composition groups in each condition.
TT performance was not significantly different between LF and HF at any time point during both recovery conditions (Table 3). Following HIIT, TT total work was significantly lower than baseline (P<0.01, CON $\eta^2=0.62$, CWI $\eta^2=0.67$) in LF and HF during both conditions. TT total work increased from post-HIIT to post-recovery in both body composition groups for both recovery conditions. The magnitude of this increase was significantly greater in HF compared with LF (P=0.027, $\eta^2=0.24$) in the CWI condition (Figure 2B).

There were no significant differences in most CMJ performance variables between body composition groups across condition and time (Table 4). Peak force per unit of body weight for IMTP was not significantly different between body composition groups in either recovery condition at baseline (CON: LF 20.1±2.6, HF 18.3±3.8; CWI: LF 19.8±3.4, HF 18.1±3.1 N/Kg). The change in IMTP peak force from baseline to post-HIIT tended to be positive in LF and negative in HF although not significantly different between groups. There was a trend for the change in IMTP peak force from post-HIIT to post-recovery to be larger in LF (-7%) compared to HF (-2%), however this was not significantly different.

Baseline HR was not different between body composition groups in each condition (CON: LF 68±8, HF 67±8, CWI: LF 68±8, HF 66±12 bpm). HR increased significantly (P<0.001, CON $\eta^2=0.98$, CWI $\eta^2=0.95$) post-HIIT (CON: LF 173±13, HF 170±10, CWI: LF 172±11, HF 171±11 bpm) however this was not significantly different between body composition groups in each condition.

A significant reduction in mean $T_{sk}$ during CWI was observed, with $T_{sk}$ reaching its lowest temperature at 15 min of CWI (LF 17.7±0.6, HF 17.4±0.5°C, P<0.001, $\eta^2=0.97$). There were no significant differences in $T_{sk}$ between body composition groups at any time-point in both recovery conditions. BSA had no effect on $T_{sk}$ change accounting for only 6.6% (CWI) and 9.9% (CON) of the variation in $T_{sk}$ change overtime. $T_{sk}$ peak-drop (LF -9.2±1.4, HF -9.1±0.6°C) in the CWI condition was not different between body composition groups.
A significant increase in $T_c$ from baseline to immediately post-HIIT was observed in both conditions ($P<0.05$) (Figure 3). There were no significant differences in $T_c$ between body composition groups during CON, however $T_c$ was significantly lower during CWI in LF compared to HF from 10-40 min post-recovery ($P<0.05$). BSA accounted for only 3.2% (CWI) and 5.8% (CON) of the variation in $T_c$ change as compared to group (LF and HF) accounting for 20.3% (CWI) and 1.8% (CON) of the change in $T_c$ over time. Significant differences between body composition groups were observed for lowest post-CWI $T_c$ (LF $36.10\pm0.61$, HF $36.83\pm0.63$ C, $P=0.013$, $d=1.78$), peak-drop (LF $-2.15\pm0.51$, HF $-1.28\pm0.77$ C, $P=0.006$, $d=-1.33$), after-drop (LF $-1.03\pm0.61$, HF $-0.66\pm0.10$ C, $P=0.050$, $d=-0.85$) and the recovery-drop of $T_c$ (LF $-1.11\pm0.30$, HF $-0.56\pm0.42$ C, $P=0.012$, $d=-1.51$).

TS increased significantly ($P<0.001$, CON $\eta^2=0.76$, CWI $\eta^2=0.88$) following HIIT and then significantly decreased ($P<0.001$) from the end of HIIT to the end of recovery for both body composition groups during both conditions (Figure 3). During the CON condition, TS returned to baseline after 15 min of recovery. In the CWI trial, TS was significantly lower ($P<0.001$) than baseline after 15 min of recovery and remained below baseline until the end of the 40 min passive recovery period. During CWI, TS was significantly lower in LF compared to HF from 10-40 min post-recovery. BSA accounted for only 4.0% (CWI) and 1.7% (CON) of the variation in TS change as compared to group (LF and HF) accounting for 11.0% (CWI) and 6.0% (CON) of the change in TS over time.

There were no significant differences in perceived TQR, soreness or fatigue between LF and HF at any time point in both CON and CWI conditions. There was also no significant difference in rating of perceived exertion (RPE) during the TT between LF and HF at any time point for both the CON and CWI conditions.

In response to CWI, large significant correlations (Figure 4) were observed between $T_c$ peak-drop and body composition variables (percent body fat, fat mass, body mass index, sum
of seven skinfolds, body surface area and body surface area to mass ratio). There were no significant correlations with T\(_c\) responses during the CON trial.

A significant correlation between the T\(_c\) percent recovery-drop and the percent change in TT work from post-HIIT to post-recovery was observed (Figure 5). There were no significant correlations between T\(_c\) percent change and CMJ or IMTP percent change, or between T\(_c\) peak-drop, T\(_c\) after-drop or any performance measure.

**DISCUSSION**

The present study aimed to compare the thermal and performance responses to CWI between two groups differing in relative body fat composition. The primary findings of the present study were: 1) individuals with lower body fat responded to CWI with greater decrements in T\(_c\) and lower perceived thermal comfort compared to higher fat individuals; 2) the reduction in T\(_c\) that occurred following CWI correlated with a reduction in the recovery of TT performance after high intensity exercise; 3) the magnitude of TT performance recovery was impaired in low fat subjects following CWI; and 4) CMJ and IMTP performance was not significantly different between body composition groups at any time-point in either condition.

Body fat is known to modulate thermogenic responses to extreme temperatures,\(^{17}\) and previous research has found body fat to influence the decline in T\(_c\) following post-exercise CWI.\(^{18}\) The present study observed significant correlations between the T\(_c\) peak-drop and measures of body fat across all subjects (Figure 4). When separated into HF and LF groups, T\(_c\) was significantly lower in LF from 10 min post-recovery until 40 min post-recovery (Figure 2). Supporting previous findings that low fat individuals have significantly lower T\(_c\) 10-30 min following CWI where there was no prior exercise.\(^{13}\) Together, these two studies demonstrate that regardless of the temperature gradient between body and water, body fat is an effective insulator impeding the decline in T\(_c\).
In addition to measures of body fat, BSA:M may also be an important factor in determining an individual’s response to cooling. Indeed, Glickman-Weiss, et al. 16 found no difference in Tc responses between low and high fat males, indicating that the similar BSA:M between the groups may have offset the differences in body fat. In the present study, BSA:M was higher in the LF group (Table 1) supporting the theory that a larger BSA:M facilitates heat exchange. Additionally, the present study identified a strong correlation between BSA:M and Tc peak-drop, whereby the greater the BSA:M the greater the decrement in Tc, which is in agreement with our previous research.30 It should be noted that our covariate analysis indicates that the effects of body fat percentage on Tc are largely independent of any effect of BSA, indicating that both physique characteristics may need to be taken into consideration when optimising individualised CWI protocols. Future research should aim to determine the combined effect of these body composition variables and how they interact to impact temperature and performance in response to post-exercise CWI. This suggested examination of a wider range of body compositions will enable findings to be extrapolated to a wider group of athletes.

Primarily, CWI enhances recovery by reducing Tc and tissue temperatures, which is thought to initiate a chain of events ultimately leading to reductions in thermal and cardiovascular strain, delayed onset muscle soreness and secondary exercise induced muscle damage.12 Whilst reducing core and tissue temperature has been suggested as the predominant mechanism of CWI leading to enhanced recovery,12 the magnitude of reduction required for optimally enhancing performance recovery remains unknown. Correlations from the present study suggest that the greater the percentage change in Tc the greater the decrement in performance (Figure 5); such that when the reduction in Tc was greater than 2.5%, CWI had either a negligible or detrimental impact on TT performance. This finding is supported by the negative correlation between the change in Tc and the change in performance observed by
To conclude, these studies demonstrate that there is an optimal cooling threshold and when this threshold is exceeded there is either a negligible or negative effect on performance recovery. Previous research has identified post-exercise CWI to be an effective strategy to maintain TT performance. However, in the present study TT performance was only maintained in the HF group. It is likely that the LF group did not experience a similar maintenance of TT performance due to the greater cooling effect observed following CWI, suggestive of overcooling.

While this hypothesised optimal cooling threshold appears to hold true for TT performance, the same does not appear to apply to all types of exercise performance, in particular shorter duration explosive muscle function. The present study examined a number of aspects of muscle function (CMJ, IMTP) to gain a broader understanding of the effect of CWI on performance. Previous research has shown that CWI is effective for restoring muscle performance in stretch-shortening activities in the days following exercise, but is ineffective for short-term restoration of force generation. The findings of the present study support these observations. The CMJ and IMTP performance measures did however show high variability across subjects which is likely related to the subject population. The subjects utilised in this study were highly trained cyclists and triathletes which is a strength for TT performance but due to these subjects having little to no habituation to the CMJ and IMTP movement tasks it is also a weakness of the study. Future research is required to fully understand the impact of CWI on the recovery of different types of performance.

CONCLUSION AND PRACTICAL APPLICATIONS

The present study highlights the importance of considering differences in body composition (particularly body fat and BSA:M) when prescribing CWI protocols, and reinforces the potential negative impact of overcooling. Furthermore, a relationship between
T<sub>c</sub> reduction and the recovery of performance following post-exercise CWI was identified. Future research should also examine how this relationship may change under different performance scenarios (e.g. endurance vs sprint), environmental conditions (e.g. heat vs cold) and time frames (e.g. minutes vs hours post-immersion). CWI is a useful recovery strategy to enhance thermal, perceptual and performance outcomes when prescribed correctly, however protocols that consider individual differences in body composition may provide the greatest benefit to post-exercise recovery and subsequent performance.
REFERENCES


Figure 1: Schematic representation of the experimental design and trial protocol. DXA = dual energy x-ray absorptiometry scan, 3D scan = three dimensional body scan, skinfolds = sum of seven skinfolds, HIIT = high intensity interval test, CMJ = countermovement jump, IMTP = isometric mid-thigh pull, VO$_2$ max = maximal oxygen uptake test, TT = time trial, Famil = familiarisation, CON = control, CWI = cold water immersion.
Figure 2: Percent change in time trial work (mean ± SD) A: from baseline to post-HIIT, B: from post-HIIT to post-recovery. * Significant difference between body composition groups (P<0.05). BAS = baseline, PEX = post-HIIT, PREC = post-recovery, CON = control, CWI = cold water immersion, LF = low fat, HF = high fat.
**Figure 3:** Core temperature and thermal sensation (mean ± SD) responses to control (CON) and cold water immersion (CWI). HIIT = high intensity interval test, Rec = recovery intervention. * Significant difference between LF and HF (P<0.05)
Figure 4: Correlation between body composition variables and core temperature ($T_c$) peak-drop. $r \pm 90\%$ confidence limits. ▲ = CON, Δ = CWI. %BF = percentage body fat, BMI = body mass index, LM = lean mass, FM = fat mass, Sum7 = sum of 7 skinfolds, BSA = body surface area, BM = body mass, BSA:M = body surface area to mass ratio. CON = control, CWI = cold water immersion. * significant correlation ($P<0.05$)
**Figure 5:** Correlation between core temperature (T_c) percent recovery-drop and percentage change in time trial total work from post-HIIT until post-recovery. $r = 0.52$, $P = 0.03$ ○ = low fat group, ● = high fat group.
Table 1: Subject characteristics.

<table>
<thead>
<tr>
<th>Subject characteristic</th>
<th>Low Fat (≤12%)</th>
<th>High Fat (≥18%)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>n=10</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (yrs.)</td>
<td>29.3±7.2</td>
<td>34.9±7.0</td>
<td>.094</td>
</tr>
<tr>
<td>(\text{VO}_2\max)\ (L/min)</td>
<td>4.7±0.4</td>
<td>4.6±0.5</td>
<td>.744</td>
</tr>
<tr>
<td>PPO (W)</td>
<td>341.2±38.5</td>
<td>333.3±38.7</td>
<td>.661</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>183.8±5.6</td>
<td>179.9±9.6</td>
<td>.281</td>
</tr>
<tr>
<td>Body mass (kg) #</td>
<td>72.8±5.7*</td>
<td>84.6±9.1</td>
<td>.003</td>
</tr>
<tr>
<td>Percent body fat (%)</td>
<td>9.5±2.2*</td>
<td>24.5±5.5</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Fat mass (kg) #</td>
<td>6.7±1.8*</td>
<td>20.2±5.9</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Lean mass (kg)</td>
<td>63.6±4.8</td>
<td>62.2±6.4</td>
<td>.590</td>
</tr>
<tr>
<td>BMI (cm/kg)</td>
<td>21.5±1.3*</td>
<td>26.1±2.5</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Sum of 7 skinfolds (mm)</td>
<td>41.8±10.6*</td>
<td>97.8±27.6</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>BSA (m(^2))</td>
<td>1.9±0.1*</td>
<td>2.0±0.1</td>
<td>.008</td>
</tr>
<tr>
<td>BSA:M (m(^2)/Kg)</td>
<td>0.026±0.001*</td>
<td>0.023±0.001</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

BMI = body mass index, \(\text{VO}_2\max\) = maximal oxygen uptake, PPO = peak power output, BSA = body surface area, BSA:M = body surface area to mass ratio. *Significant difference between body composition groups (\(P<0.05\)). # = values used to calculate percent body fat.
Table 2: HIIT protocol.

<table>
<thead>
<tr>
<th>Elapsed time (min)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm-up</td>
<td>0-10 4 min Easy (50-65% PPO)</td>
</tr>
<tr>
<td></td>
<td>3 min Moderate (65-72.5% PPO)</td>
</tr>
<tr>
<td></td>
<td>3 min Threshold (72.5-80% PPO)</td>
</tr>
<tr>
<td>Set 1 – Short sprints</td>
<td>10-16 3 × 6s max, 114 sec recovery</td>
</tr>
<tr>
<td></td>
<td>Sprint 1: 80% max (level 6)</td>
</tr>
<tr>
<td></td>
<td>Sprint 2: 100% max (level 6)</td>
</tr>
<tr>
<td></td>
<td>Sprint 3: 100% max (level 10)</td>
</tr>
<tr>
<td>Recovery 1</td>
<td>16-20 4 min recovery at 50 W</td>
</tr>
<tr>
<td>Set 2 – Long sprints</td>
<td>20-24 4 × (20 s max, 40 s recovery)</td>
</tr>
<tr>
<td>Recovery 2</td>
<td>24-31 7 min recovery at 50 W</td>
</tr>
<tr>
<td>Set 3 – Repeat Sprints</td>
<td>31-37.5 13 x (20 s max, 10 s recovery)</td>
</tr>
<tr>
<td>Recovery 3</td>
<td>37.5-44.5 7 min recovery at 50 W</td>
</tr>
<tr>
<td>Set 4 – Pursuit effort 1</td>
<td>44.5-48.5 4 × (45 s at 250 W, 15 s max)</td>
</tr>
<tr>
<td>Recovery 4</td>
<td>48.5-55.5 7 min recovery at 50 W</td>
</tr>
<tr>
<td>Set 5 – Pursuit effort 2</td>
<td>55.5-59.5 3 × (1 min at 250 W, 20 s max)</td>
</tr>
<tr>
<td>Recovery 5</td>
<td>59.5-66.5 7 min recovery at 50 W</td>
</tr>
<tr>
<td>Passive rest</td>
<td>66.5-67 30 s passive rest</td>
</tr>
<tr>
<td>Set 6 – Time Trial effort</td>
<td>67-71 4 min TT</td>
</tr>
<tr>
<td>Cool down</td>
<td>71-73 2 min recovery at 50 W</td>
</tr>
</tbody>
</table>

PPO = peak power output, Max = maximal voluntary effort, Level = Wattbike air-resistance level, TT = time trial.
Table 3: Time trial performance.

<table>
<thead>
<tr>
<th></th>
<th>Low fat (n = 10)</th>
<th>High fat (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline (mean ± SD)</td>
<td>Post-HIIT (mean ± SD)</td>
</tr>
<tr>
<td><strong>Total work (Kj)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CON</strong></td>
<td>90.9 ± 12.6</td>
<td>83.5 ± 12.1*</td>
</tr>
<tr>
<td><strong>CWI</strong></td>
<td>90.7 ± 11.1</td>
<td>83.1 ± 11.7*</td>
</tr>
<tr>
<td><strong>P value</strong></td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td><strong>Total Distance (km)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CON</strong></td>
<td>3.1 ± 0.2</td>
<td>3.0 ± 0.2*</td>
</tr>
<tr>
<td><strong>CWI</strong></td>
<td>3.1 ± 0.1</td>
<td>3.0 ± 0.2*</td>
</tr>
<tr>
<td><strong>P value</strong></td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td><strong>Average Power (W)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CON</strong></td>
<td>379.0 ± 52.6</td>
<td>348.4 ± 50.3*</td>
</tr>
<tr>
<td><strong>CWI</strong></td>
<td>378.5 ± 46.3</td>
<td>346.5 ± 49.1*</td>
</tr>
<tr>
<td><strong>P value</strong></td>
<td>0.20</td>
<td></td>
</tr>
</tbody>
</table>

CON = control, CWI = cold water immersion. * Significantly different to baseline (P < 0.05). # Significantly different to post-HIIT (P < 0.05).
Table 4: Countermovement jump performance.

<table>
<thead>
<tr>
<th></th>
<th>Force (N/Kg)</th>
<th>Velocity (m/s)</th>
<th>Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LF (mean ± SD)</td>
<td>HF (mean ± SD)</td>
<td>LF (mean ± SD)</td>
</tr>
<tr>
<td>CON</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>baseline</td>
<td>20.1 ± 1.5</td>
<td>20.4 ± 1.9</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>post-exercise</td>
<td>20.1 ± 0.8</td>
<td>20.0 ± 1.7</td>
<td>2.3 ± 0.3</td>
</tr>
<tr>
<td>post-recovery</td>
<td>20.0 ± 1.1</td>
<td>19.9 ± 1.1*</td>
<td>2.5 ± 0.3</td>
</tr>
<tr>
<td>Weighted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>baseline</td>
<td>17.0 ± 0.8</td>
<td>16.6 ± 1.3</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>post-exercise</td>
<td>17.3 ± 0.6</td>
<td>16.8 ± 1.4</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>post-recovery</td>
<td>17.2 ± 0.7*</td>
<td>16.7 ± 1.2</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>CWI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>baseline</td>
<td>20.2 ± 1.2</td>
<td>20.0 ± 1.8</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>post-exercise</td>
<td>20.1 ± 1.2</td>
<td>19.8 ± 1.7</td>
<td>2.4 ± 0.2*</td>
</tr>
<tr>
<td>post-recovery</td>
<td>19.1 ± 1.2*</td>
<td>19.5 ± 2.3</td>
<td>2.3 ± 0.2*</td>
</tr>
<tr>
<td>Weighted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>baseline</td>
<td>17.1 ± 0.9</td>
<td>16.8 ± 1.5</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>post-exercise</td>
<td>17.2 ± 0.8</td>
<td>16.9 ± 1.5</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>post-recovery</td>
<td>16.5 ± 1.5</td>
<td>16.5 ± 1.5</td>
<td>1.8 ± 0.1</td>
</tr>
</tbody>
</table>

LF = low fat, HF = high fat, CON = control, CWI = cold water immersion, * Significantly lower than baseline (P < 0.05). # Significantly lower than post-exercise (P < 0.05).
Note. This article will be published in a forthcoming issue of the International Journal of Sports Physiology and Performance. The article appears here in its accepted, peer-reviewed form, as it was provided by the submitting author. It has not been copyedited, proofread, or formatted by the publisher.

Section: Original Investigation

Article Title: Core Temperature Responses to Cold-Water Immersion Recovery: A Pooled-Data Analysis

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Journal: International Journal of Sports Physiology and Performance

Acceptance Date: December 12, 2017

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DOI: https://doi.org/10.1123/ijspp.2017-0661
Title

Core temperature responses to cold-water immersion recovery: a pooled-data analysis

Submission type

Original Investigation

Authors

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Running head: Cold water immersion and core temperature

Abstract word count: 246

Text-only word count: 3473

Number of figures and tables: Figures = 3, Tables = 2
ABSTRACT

**Purpose:** To examine the effect of post-exercise cold water immersion (CWI) protocols compared with control (CON), on the magnitude and time-course of core temperature (T_c) responses. **Methods:** Pooled data analyses were used to examine the T_c responses of 157 subjects from previous post-exercise CWI trials in our laboratories. CWI protocols varied with different combinations of temperature, duration, immersion depth and mode (continuous vs intermittent). T_c was examined as a double difference (ΔΔT_c), calculated as the change in T_c in CWI condition minus the corresponding change in CON. The effect of CWI on ΔΔT_c was assessed using separate linear mixed models across two time components (Component 1: immersion, and Component 2: post-intervention). **Results:** Intermittent CWI resulted in a mean decrease in ΔΔT_c that was 0.254±0.10°C (estimate ± SE) greater than continuous CWI during the immersion component (P=0.022). There was a significant effect of CWI temperature during the immersion component (P=0.056), where reductions in water temperature of 1°C resulted in decreases in ΔΔT_c of 0.03±0.01°C. Similarly, the effect of CWI duration was significant during the immersion component (P=0.01), where every 1 min of immersion resulted in a decrease in ΔΔT_c of 0.02±0.01°C. The peak difference in T_c between the CWI and CON interventions during the post-immersion component occurred at 60 min post-intervention. **Conclusion:** Variations in CWI mode, duration and temperature, may have a significant effect on the extent of change in T_c. Careful consideration should be given to determine the optimal amount of core cooling before deciding which combination of protocol factors to prescribe.

**Key Words:** Hydrotherapy, performance, exercise, ice-bath, protocol-variance.
INTRODUCTION

Cold water immersion (CWI) is a widely practiced recovery modality aiming to reduce fatigue and facilitate post-exercise recovery. It is thought that the combination of cold temperature and hydrostatic pressure promotes reductions in tissue temperatures and blood flow, facilitating subsequent reductions in thermal and cardiovascular strain, oedema, inflammation and pain. The dominant mechanism by which CWI is believed to be effective for acute recovery is its ability to ameliorate hyperthermia and the subsequent central nervous system mediated fatigue. Indeed, previous research has attributed the enhanced recovery of maximal voluntary contraction force to faster return of central activation which is the resulting from of larger CWI induced reductions in core temperature ($T_c$). With hyperthermia mediated fatigue being a key fatiguing factor for many forms of exercise, a greater understanding of the impact of CWI on $T_c$ (as an indicator of hyperthermia) will enhance the effectiveness of CWI.

There is increasing evidence to support the notion that CWI enhances both short- and long-term recovery of performance, particularly for endurance and team sports, there are also several studies that have shown CWI to have either a negligible or detrimental effect on performance. With consideration of this variance in findings, it may be that CWI is not suitable for all post-exercise contexts, and the exercise mode performed prior to immersion, in addition to the time frame available and the environment in which exercise is performed (e.g. hot vs. cool vs. thermoneutral) are key factors influencing the effectiveness of CWI. Endurance based performance has been shown to be most responsive to CWI; however, there is still considerable variability across studies assessing endurance performance. For example, while a number of studies have found CWI to be effective for maintaining cycling time-trial performance in a subsequent exercise bout performed 40 min to 3 days post-CWI, others observed a decrease in time-trial performance over the same time frame. The factors
responsible for this large variation in findings across the current literature are unclear, and as such, there is substantial debate as to the true efficacy of CWI as a recovery strategy.\textsuperscript{1,4}

Variation in the physiological and performance recovery responses to CWI is likely to depend the degree of cooling that can be achieved which is a result of the initial interaction between the protocol utilised and the characteristicistics of the individual (e.g. body composition, age, sex, ethnicity, etc).\textsuperscript{4} Understanding the optimal degree of cooling is important as too little cooling may cause CWI to be less effective due to limited reductions in muscle temperature ($T_m$) and $T_c$.\textsuperscript{13} Conversely, too much cooling may lead to a reduction in muscle contractile force.\textsuperscript{14} Current CWI protocols administered in practice vary in terms of the water temperature, duration, depth and mode of immersion, and the optimal combination of these factors remains unknown.\textsuperscript{4,14,15} The interaction between each of these protocol factors is complex and previous research has shown the same degree of $T_c$ change (0.4°C) in response to different CWI protocols (e.g. 5 min, 14°C, whole body immersion\textsuperscript{16} vs. 5 min, 10°C, leg only immersion\textsuperscript{17}). However, it remains unknown whether the thermal stress applied by the temperature stimulus, the duration of exposure to the cold stimulus, the depth of immersion and body surface area exposed to the cold stimulus, or the change in temperature gradient by moving in and out of the water during intermittent immersion has the greatest impact on $T_c$ responses.

Recently it has been suggested that continuous immersion in water temperatures between 11-15°C for 11-15 min are optimal for reducing muscle soreness.\textsuperscript{15} However, the most effective approach for reducing $T_c$ and exercise-induced hyperthermia remains unknown, and further research is required to understand how each factor contributes to $T_c$ change.\textsuperscript{4} With previous research showing that the change in $T_c$ is related to a change in performance,\textsuperscript{3,9,18} it is important to gain a greater understanding of $T_c$ responses as it will enable CWI protocols to be optimised and ultimately improve the restoration of performance for individual athletes. Therefore, the aims of the present study were twofold: 1) to conduct a pooled analysis across a
large data set to examine the impact of variability in different CWI protocol factors on $T_c$ change relative to a control condition; and 2) to characterise the time-course of $T_c$ responses to post-exercise CWI both during immersion and post-immersion.

METHODS

Study Design

This study adopted a pooled analysis approach using data from 157 male subjects from 13 previous investigations of post-exercise CWI in our laboratories. Data were assessed using two respective linear mixed models based on different time components. The first component examined the change in $T_c$ between the end of exercise and the end of the CWI/Control (CON) recovery intervention (Component 1: immersion). The second component examined the post-recovery change only and is defined as the difference in $T_c$ between the end of the CWI/CON recovery intervention and each of the available post-intervention time-points (Component 2: post-intervention).

Data Sources

Individual de-identified raw data were collated from 13 previous studies by our groups for inclusion in this pooled analysis (Table 1). Criteria for inclusion were: 1) use of a cross-over controlled design, 2) included seated passive CON condition, 3) CWI performed post-exercise, 4) measured $T_c$ via rectal thermister or telemetric pill, and 5) exercise resulted in a significant increase from baseline in mean $T_c$ ($\geq 38.0^\circ$C). Studies with missing data (where raw data could not be accessed) or without $T_c$ measures immediately post-exercise and/or post-recovery were excluded (Figure 1). There were no specific criteria for type of exercise utilised; however, 11 studies examined cycling$^{8,10,11,19-26}$ and two examined sprint running$^3,27$. Of the 13 studies included, ten are published in academic journals$^{3,8,10,11,18,19,21,23,26,27}$ and three in PhD theses.$^{20,24,25}$
Subjects

De-identified raw data were extracted from 13 studies, providing data on 157 trained male subjects (Table 2). Subjects across all studies were classified as well-trained with 94 indentifying as predominantly participating in cycling or triathlon, 29 in team sports, leaving 36 with an unspecified sporting background.

Cold water immersion protocol combinations

CWI protocols varied across studies, with seven different temperatures, eight immersion durations, three depths and two modes of immersion utilised (Table 1), making a total of 336 possible combinations of which 16 were utilised. Of the 13 studies included, nine studies used just one CWI protocol,\(^\text{3,8,10,18,19,21,23,24,27}\) two studies used two protocols,\(^\text{25,26}\) one study included three protocols,\(^\text{11}\) and another study used four\(^\text{20}\) different protocols giving a total of 20 within-study-protocol combinations. Of these protocols, four were used in two studies so that there were only 16 of the 336 possible CWI protocols represented across the 13 studies. Further, there were only 15 (out of a possible 56) combinations of duration and temperature used, with just one combination used at more than one immersion depth. Additionally, all 15 of these combinations were associated with just one of the two modes, continuous or intermittent, resulting in partial confounding between the four components of the CWI protocols so that it is not possible to completely separate the effects of the various (protocol) factors. For analysis and to allow comparisons between studies, immersion depth was converted into a predicted body-surface-water-contact area of 1.3 m\(^2\) for waist-depth, 1.6 m\(^2\) for chest-depth, and 1.8 m\(^2\) for neck-depth based on normative measurements of an average, and therefore comparable, male.\(^\text{28}\) The offset time between the end of exercise and the commencement of CWI also varied, and there were seven different offset times used across the 13 studies (Table 1).
Calculation of the change in Core Temperature ($T_c$)

$T_c$ was either measured by rectal thermistor$^{8,10,11,18,21,23,24}$ or by sensor telemetry.$^{3,20,25-27}$ $T_c$ was measured at different time-points across the 13 studies (Table 1), including immediately post-exercise, immediately post-recovery (0 min) and at 13 post-recovery time-points (5, 10, 15, 20, 30, 40, 60, 90, 120, 150, 180, 210, 240 min post-intervention). Two of the studies$^{3,21}$ recorded just two $T_c$ values for each participant; one at the end of exercise and the other at the end of CWI, and therefore were only included in the immersion component analysis. The other 11 studies recorded $T_c$ values at additional times following the completion of CWI and were therefore included in the post-intervention component analysis. One study controlled post-exercise $T_c$ to ensure it was equal across subjects and trials,$^{23}$ while the remaining 12 studies did not attempt to control post-exercise $T_c$. Regardless, there was no significant difference between trials (CWI vs CON) for each participant, as determined by initial t-test analysis. The $T_c$ response was calculated in each of the models as a double difference ($\Delta\Delta T_c$), whereby the change in $T_c$ in the CWI condition minus the corresponding difference under the control condition relative to post-exercise in Component 1 and immediately post-recovery in Component 2, (e.g. $\Delta\Delta T_c = (\text{CWI post-exercise } T_c - \text{CWI post-recovery } T_c) - (\text{CON post-exercise } T_c - \text{CON post-recovery } T_c)$). A negative $\Delta\Delta T_c$ indicates that the change in $T_c$ is greater in the CWI condition compared to the control.

Statistical analysis

The statistical analysis consisted of two, distinct components. The first component (immersion) considered the $\Delta\Delta T_c$ changes from the end of exercise to the end of the recovery treatment, while the second component (post-intervention) considered the $\Delta\Delta T_c$ changes following the recovery intervention. For each component, a linear mixed model was used with CWI protocols (combination of duration, temperature, depth and mode) and the offset from the end of exercise to the start of the CWI treatment treated as a fixed effects and either study-
protocol (i.e. the different protocols within a study were essentially treated as being different studies) or subject as random effects for components 1 and 2, respectively. Five of the 11 studies with data following the CWI treatment period included more than one post-CWI observation and the models fitted to these data made allowance for possible autocorrelation within subjects. To fit these models, it was necessary to treat the subjects that used more than one protocol (within a study) as though they were different subjects. In addition to the effect of CWI treatment, it was also of interest to evaluate how the ΔΔTc varied with time, post-recovery. When this time was fitted as a (fixed effect) factor (only 13 time points were used in the studies), the relationship was deemed appropriate to then subsequently model using regression splines. All models were fitted using the lme or gamm components of the mgcv package available in R. The significance level was P≤0.05 and data are reported as mean±standard deviation or estimate±standard error.

RESULTS

Component 1 – Immersion

Across all subjects average post-exercise Tc was 38.56±0.60°C and immediately post-intervention was 37.72±0.53°C. The effects of CWI time, temperature and mode are illustrated in Figure 2 which gives the estimated overall responses for each of the 20 study-protocol combinations used in the 13 studies. Intermittent CWI results in a significantly (P=0.02) greater decrease in ΔΔTc 0.254±0.10°C (estimate ± SE) than that obtained with continuous CWI. The effect of CWI temperature can be described by a significant (P=0.05) linear regression with a coefficient of 0.03±0.01°C. That is, for each reduction in CWI temperature of 1°C, ΔΔTc is estimated to decrease on average by 0.03°C. The effect of CWI duration was significant (P=0.01), with a decrease of 0.02±0.01°C ΔΔTc for each additional minute of CWI immersion. Neither depth (P=0.19) nor offset time (P=0.90) had a significant effect on ΔΔTc.
The inclusion of the study-protocol in the model had a minimal effect on the parameter estimates, though it did result in slight increases in the standard errors and hence slight increases in the p-values. The residual standard deviation, which includes the between-subject variation not accounted for by the fitted model, and indicates the variation that was observed between the changes in individual subjects, was estimated to be 0.444°C.

**Component 2 – Post-intervention**

The effect of offset time was significant (P=0.00), with an increase of 0.01°C $\Delta T_c$ for each minute increase in offset time. Further, the effect of post-recovery time was also significant (P<0.001) and was adequately described by a cubic regression spline. Specifically, peak difference between CWI and CON occurred at ~60 min post-intervention; following this $\Delta T_c$ slowly increased until there was no impact of the intervention (Figure 3). Also displayed in Figure 3 are estimates of the effect of post-recovery time when it was treated as a factor (with 13 levels, the number of different times used in the studies). Other effects such as CWI type (intermittent or continuous), duration, temperature and depth were also evaluated, but none of them made a (statistically) significant contribution.

The inclusion of within subject autocorrelation in the model had an appreciable effect on the parameter estimates with the autocorrelation being highly significant (P<0.001). The residual standard deviation, which includes within-subject variation not accounted for by the fitted model, was estimated to be 0.36°C.

**DISCUSSION**

The present study aimed to understand the implications of varying the temperature, duration, depth and mode of CWI protocols on $T_c$, and to identify the ensuing time-course of $T_c$ responses based on these post-exercise CWI protocol variations. The main findings were:

1) that intermittent protocols resulted in a significantly greater decrement in $T_c$ compared to continuous protocols for the $T_c$ change during immersion; 2) decreasing water temperature and
increasing duration of CWI resulted in a significant decrease in ΔΔT_c during immersion; 3) the longer the offset time (end of exercise to immersion commencement), the smaller the change in T_c post-recovery; and 4) the peak difference in T_c between CON and CWI protocols occurred at ~60 min post-recovery, irrespective of protocol mode.

Reported post-exercise CWI protocols vary substantially^4,15 and while CWI is widely utilised by athletes, a lack of consensus as to the best protocols for different sport/athlete scenarios remains.^14 Accordingly, the present study combined the data from a range of studies representing the variety of protocols currently utilised to determine the impact of different combinations and interaction of these factors on the change in T_c. One of the major findings of the present study was that intermittent CWI protocols appear to be more effective in lowering T_c compared to continuous CWI. It may be postulated that the lower T_c observed, on average, in response to intermittent CWI might be related to the frequent change in thermal gradient occurring each time the participant moves between the cold water and the warmer air. This frequent change may have led to repeated reactive hyperaemia responses where both skin and muscle blood flow increases when the participant moves out of the pool after a period of cold-induced vasoconstriction and ischemia which occurs during immersion.^31 This theory is supported by the findings of Romet^32 and Seo, et al. ^33 who found that following removal from CWI, vasodilation occurred in the extremities and greater conductive heat transfer occurred due to the return of cooler blood to the central circulation. Nevertheless, as only three studies utilised intermittent protocols, the conclusions which can be drawn from these data need to be confirmed by future research.

Often in practical settings, the duration and depth of CWI are determined by the water temperature based on athlete tolerance; thus, these variables were also examined in the present study given their ecological interactions in many protocols. Although it has been suggested that the physiological changes in response to post-exercise CWI are temperature dependent,^14 the
way these factors interact with each other and which factor has the greatest impact on $T_c$ responses remains unknown.\textsuperscript{4} Both temperature and duration were found to have a highly significant impact on $\Delta \Delta T_c$. The current study found that CWI temperature led to a decrease in $\Delta \Delta T_c$ of 0.025°C for every 1°C reduction in water temperature, and that CWI duration led to a reduction in $\Delta \Delta T_c$ of 0.018°C for every additional minute of immersion time. Collectively, colder water temperatures and greater immersion durations lead to a greater reduction in $T_c$ compared to an equivalent duration CON. However, such an effect was only observed for continuous immersion protocols, as no evidence of a duration effect was apparent for intermittent protocols given the small range of intermittent protocols included in the analyses. The depth of immersion was not significant and highly confounded with the other protocol factors. Increasing immersion depth is believed to enhance responses to CWI by increasing hydrostatic pressure as well as exposing a greater body surface area for thermal exchange via convection to occur.\textsuperscript{4} The impact of hydrostatic pressure was recently examined by comparing seated versus standing CWI, with no significant difference reported between the two conditions, suggesting water temperature may be of greater importance.\textsuperscript{34} Given the absence of studies examining the effect of different immersion depths on $T_c$ responses to post-exercise CWI, further research is required to fully determine the impact of varying CWI depth.

Post-exercise CWI has been shown to significantly reduce $T_c$; however, the extent of this reduction is highly variable, and the time-course of change remains to be fully elucidated.\textsuperscript{4} The present study examined the change in $T_c$ during and post-immersion as two separate components as it was recognised that the rate of $T_c$ change would be vastly different depending on the thermal environment the body is placed in. The present study found that the sooner CWI is commenced post-exercise the greater the reduction in post-immersion $T_c$ will be. This may be due to $T_c$ and blood flow being elevated at the end of exercise, therefore, increasing the thermal gradient between the body and the water and thermal exchange between blood and
body tissues. It was also found that when examining $T_c$ change post-recovery, the greatest difference between CWI and CON occurred 60 min post-recovery (Figure 2). This novel finding highlights the importance of this time period post-immersion, and it highlights the potentially negative effect of a hot shower post-immersion. A hot shower immediately post-immersion is a common practice of some athletes which may prevent the after-drop in $T_c$ therefore, potentially limiting the effectiveness of CWI on core cooling. However, with only three studies examining $T_c$ change for $\geq 60$ min post-immersion, the estimates of $\Delta \Delta T_c$ become weaker as time increases, potentially limiting the strength of conclusions which can be drawn.

This prolonged decrease in $T_c$ after CWI may have practical implications for repeat-performance and should be considered when prescribing protocols. It is hypothesised that the optimal protocol parameters will vary depending on recovery needs of the athlete, which will be determined by the specific type of fatigue (e.g. central nervous system fatigue, cardiovascular fatigue, etc.), time-frame available and type of performance (e.g. endurance vs sprint) required.$^{1,4}$ It is also important to consider the environmental conditions.$^{1,35}$ For example, performing CWI during a short time-frame between endurance tasks may provide pre-cooling benefits for subsequent exercise, particularly when environmental conditions are warm or hot. However, when performance requires maximal contractions and the time-frame between repeat performances is short, CWI induced changes in body temperature will likely reduce muscular performance.$^{4,15}$

Future studies should focus on determining the exact degree of change in $T_c$ that leads to an optimal cooling effect for subsequent performance and how different CWI protocol factors work towards inducing this $T_c$ change. Future research should also look to establish the optimal cooling effect for other physiological variables such as muscle temperature and blood flow as these also have the potential to impact performance recovery. The residual standard deviations were estimated to be 0.44°C and 0.36°C for components 1 and 2, respectively.
Compared to the estimated effects of CWI, these values are relatively large which means that, while various effects have been found, on average, to be statistically significant, there is a lot of additional variation between subjects (for component 1) and within subjects (for component 2) so that it is not yet possible to deduce how individual athletes will respond to CWI.

The present pooled-data analysis study builds on a previous meta-analysis\textsuperscript{36} by examining individual responses to a range of CWI protocols and highlights the fact that responses to post-exercise CWI are highly variable and are impacted by a myriad of factors. It is not solely the dose of cooling provided by the combination of CWI temperature, duration, depth and mode that impact these responses. Other factors such as laboratory/environmental conditions, differences in exercise induced thermoregulatory stress, offset differences (i.e. time between end of exercise and start of CWI) and individual participant differences (e.g. body composition, age, sex and ethnicity) also impact responses and may explain much of the variation in the current literature. The relatively homogenous cohort examined in this pooled analysis acts to delimit several of these potentially confounding factors (e.g. sex, age, body composition), yet this may also limit the applicability of findings to other populations. The large number of factors impacting the cooling response makes attempting to predict the optimal “dose” of CWI quite difficult, especially when many combinations of factors have not been tested. Nevertheless, this study has drawn on a large data set to provide some clarity around the influence of CWI protocol mode, temperature, duration and offset differences on $T_c$ response. An understanding of how variations in these factors impact temperature change will enable future researchers to better prescribe CWI protocols, and ultimately facilitate the optimisation of performance recovery.
PRACTICAL APPLICATIONS

- Before prescribing a CWI protocol it is important to determine how much core cooling needs to be induced. For situations where more intense cooling is required, longer duration and colder water temperatures may be more effective.

- When greater reductions in $T_c$ are required, CWI should be performed as soon as possible after exercise.

- Intermittent CWI protocols are effective in reducing $T_c$ and can be used when there are a large number of athletes needing to complete CWI with limited resources (e.g. one ice bath) or when an athlete is uncomfortable with long duration CWI.

- Consideration should be given to what activities the athletes have in the 60 min post-immersion as $T_c$ continues to decrease during this period.

ACKNOWLEDGEMENTS

The authors would like to thank all of the researchers who contributed to each of the studies utilised in this analysis. The authors would like to acknowledge Dr. Andrew Govus for his assistance in the early stages of planning this study. This investigation was supported by funding from a University of the Sunshine Coast Faculty HDR research grant. The authors declare that there are no conflicts of interest in undertaking this study.
REFERENCES


24. Versey NG. *Hydrotherapy and Recovery from Exercise Induced Fatigue: Performance Effects and Mechanisms Involved [dissertation]*. University of Western Australia Research Repository: School of Sport Science, The University of Western Australia; 2012.


Figure 1: Flow chart on all relevant cold water immersion studies performed in our laboratories and the reason for exclusion
Figure 2: Estimated responses for each of the 20 study-protocol combinations used in the 13 studies. Numbers next to data points = water temperature. $\Delta T_c$ = Change in $T_c$ in CWI condition minus change in $T_c$ in CON condition
**Figure 3:** Parameter estimates and fitted spline with 95% confidence limits for the change in $T_c$ from end of intervention to each of the post-intervention time points. $\Delta \Delta T_c = \text{Change in } T_c \text{ in CWI condition minus change in } T_c \text{ in CON condition}$
Table 1: Data sources

<table>
<thead>
<tr>
<th>Study number</th>
<th>Reference</th>
<th>Number of participants</th>
<th>CWI condition(s)</th>
<th>CON condition</th>
<th>Tc method</th>
<th>Tc measurement time-points</th>
<th>Offset (EndEx to Rec0)</th>
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<th>EndEx Tc (°C)</th>
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### Core Temperature Responses to Cold-Water Immersion Recovery: A Pooled-Data Analysis

**Stephens JM et al.**

*International Journal of Sports Physiology and Performance*  
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<td>Waist</td>
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<td>R</td>
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CWI = cold water immersion, CON = control, C = continuous, I = intermittent Tc = core temperature, EndEx = immediately post-exercise, Rec0 = start of recovery intervention EndRec = immediately post-recovery, PostRec = post-recovery intervention, R = Rectal temperature, G = Gastrointestinal temperature.
Table 2: Participant characteristic in each study; mean ± standard deviation.

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<td>64.0±5.7</td>
</tr>
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<td>3</td>
<td>Peiffer et al., (2010a)</td>
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<td>Stephens et al., (2017)</td>
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<td>78.7±9.6</td>
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<td>59.7±6.2</td>
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<td>Minett et al., (2014)</td>
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<td>6</td>
<td>Vaile et al., (2008)</td>
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<td>69.9±4.8</td>
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<td>Pointon et al., (2012)</td>
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<td>8</td>
<td>Vaile et al., (2008b)</td>
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<td>Dunne et al., (2013)</td>
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<td>Stephens et al., (2017b)</td>
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<td>Halson et al., (2008)</td>
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n/a = information not available, VO$_2$ max = volume of oxygen consumption at maximum exertion