Cooling for Protection and Recovery from Exercise- and Environment-Induced Heat Stress in Medium-Fast Bowlers

Geoffrey M. Minett
Bachelor of Exercise Science (Hons)

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School of Human Movement Studies
Faculty of Education
Charles Sturt University
Bathurst NSW 2795
Australia
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Certificate of Authorship

I, Geoffrey Minett,

“I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma at Charles Sturt University or any other educational institution, except where due acknowledgment is made in the thesis Cooling for Protection and Recovery from Exercise- and Environment-Induced Heat Stress in Medium-Fast Bowlers. Any contribution made to the research by colleagues with whom I have worked at Charles Sturt University or elsewhere during my candidature is fully acknowledged.

I agree that this thesis be accessible for the purpose of study and research in accordance with the normal conditions established by the Executive Director, Library Services or nominee, for the care, loan and reproduction of theses, subject to confidentiality provisions as approved by the University.”

Signature .......................................................... Date .........................
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Publications


# Abbreviations

<table>
<thead>
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<th>Definition</th>
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<tr>
<td>ACT</td>
<td>Active Recovery</td>
</tr>
<tr>
<td>AIS</td>
<td>Australian Institute of Sport</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
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<tr>
<td>AST</td>
<td>aspartate aminotransferase</td>
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<tr>
<td>Bpm</td>
<td>Beats per Minute</td>
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<tr>
<td>CA</td>
<td>Cricket Australia</td>
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<tr>
<td>CAR</td>
<td>Central Activation Ratio</td>
</tr>
<tr>
<td>CG</td>
<td>Compression Garment</td>
</tr>
<tr>
<td>CHO</td>
<td>Carbohydrate</td>
</tr>
<tr>
<td>CHO+STR</td>
<td>Carbohydrate and Stretching</td>
</tr>
<tr>
<td>CMJ</td>
<td>Counter-Movement Jump</td>
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<tr>
<td>CNS</td>
<td>Central Nervous System</td>
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<tr>
<td>CONT</td>
<td>Control</td>
</tr>
<tr>
<td>CORT</td>
<td>Cortisol</td>
</tr>
<tr>
<td>CP</td>
<td>Constant Pace</td>
</tr>
<tr>
<td>CRP</td>
<td>C-Reactive Protein</td>
</tr>
<tr>
<td>CV</td>
<td>Coefficient of Variation</td>
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<tr>
<td>CWI</td>
<td>Cold-Water Immersion</td>
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<tr>
<td>CWT</td>
<td>Contrast-Water Therapy</td>
</tr>
<tr>
<td>DEC</td>
<td>Deception</td>
</tr>
<tr>
<td>DOMS</td>
<td>Delayed Onset Muscle Soreness</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyography</td>
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<tr>
<td>ESQ</td>
<td>Environmental Symptoms Questionnaire</td>
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<tr>
<td>Ex</td>
<td>Exercise</td>
</tr>
<tr>
<td>FABP</td>
<td>Fatty Acid Binding Protein</td>
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<td>Free Fatty Acids</td>
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<td>Glu</td>
<td>Glucose</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>H</td>
<td>Head</td>
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<tr>
<td>HH</td>
<td>Head + Hand</td>
</tr>
<tr>
<td>HHb</td>
<td>Deoxyhaemoglobin</td>
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<tr>
<td>HCO₃</td>
<td>Bicarbonate</td>
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<tr>
<td>HR</td>
<td>Heart Rate</td>
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<tr>
<td>HT</td>
<td>Half Time</td>
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<tr>
<td>HU</td>
<td>Humid</td>
</tr>
<tr>
<td>K⁺</td>
<td>Potassium</td>
</tr>
<tr>
<td>ICC</td>
<td>Intraclass Correlation</td>
</tr>
<tr>
<td>ICE</td>
<td>Ice Slurry</td>
</tr>
<tr>
<td>iEMG</td>
<td>Integrated Electromyography</td>
</tr>
<tr>
<td>IGF-1</td>
<td>Insulin-Like Growth Factor 1</td>
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<tr>
<td>IGF-BP3</td>
<td>Insulin-Like Growth Factor-Binding Protein 3</td>
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<tr>
<td>IL-1β</td>
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<td>IL-10</td>
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</tr>
<tr>
<td>INS</td>
<td>Insulin</td>
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<td>ISE</td>
<td>Intermittent-Sprint Exercise</td>
</tr>
<tr>
<td>La⁻</td>
<td>Lactate</td>
</tr>
<tr>
<td>LCG</td>
<td>Liquid Cooled Garment</td>
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<tr>
<td>LDH</td>
<td>Lactate Dehydrogenase</td>
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<td>LIST</td>
<td>Loughborough Intermittent Shuttle Test</td>
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<tr>
<td>MAP</td>
<td>Mean Arterial Pressure</td>
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<tr>
<td>Mb</td>
<td>Myoglobin</td>
</tr>
<tr>
<td>MH</td>
<td>Moderate Heat</td>
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<tr>
<td>MIX</td>
<td>Mixed-Method Cooling</td>
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<td>MS</td>
<td>Muscle Soreness</td>
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<td>MT</td>
<td>Mock Treatment</td>
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<td>MVC</td>
<td>Maximal Voluntary Contraction</td>
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<td>N</td>
<td>Normal</td>
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<tr>
<td>Na⁺</td>
<td>Sodium</td>
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<td>Ammonia</td>
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<tr>
<td>NH₄⁺</td>
<td>Ammonium</td>
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<tr>
<td>NIRS</td>
<td>Near-Infrared Spectroscopy</td>
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<td>O₂</td>
<td>Oxygen</td>
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<tr>
<td>O₂Hb</td>
<td>Oxyhaemoglobin</td>
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<tr>
<td>PCG</td>
<td>Phase Change Garment</td>
</tr>
<tr>
<td>pH</td>
<td>Potential Hydrogen</td>
</tr>
<tr>
<td>PH</td>
<td>Passive Pre-Heating</td>
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<tr>
<td>PLA</td>
<td>Placebo</td>
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<tr>
<td>PO</td>
<td>Power Output</td>
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<tr>
<td>PPO</td>
<td>Peak Power Output</td>
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<tr>
<td>PSI</td>
<td>Physiological Strain Index</td>
</tr>
<tr>
<td>Pt</td>
<td>Peak Torque</td>
</tr>
<tr>
<td>Q</td>
<td>Cardiac Output</td>
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<tr>
<td>R</td>
<td>Inter-Class Correlation</td>
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<tr>
<td>RER</td>
<td>Respiratory Exchange Ratio</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<tr>
<td>RPE</td>
<td>Respiratory Exchange Ratio</td>
</tr>
<tr>
<td>RR</td>
<td>Rate of Relaxation</td>
</tr>
<tr>
<td>RSA</td>
<td>Repeated Sprint Ability</td>
</tr>
<tr>
<td>RTD</td>
<td>Rate of Torque Development</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>SEM</td>
<td>Typical Error</td>
</tr>
<tr>
<td>SPSS</td>
<td>Statistical Package for Social Sciences</td>
</tr>
</tbody>
</table>
SV  Stroke Volume
SwR  Sweat Rate
T_b  Body Temperature
T_c  Core Temperature
T_es  Oesophageal Temperature
TEST  Testosterone
THb  Total Haemoglobin
T_mu  Muscle Temperature
T_Pt  Time to Peak Torque
T_re  Rectal Temperature
TSI  Tissue Saturation Index
T_sk  Skin Temperature
TSS  Thermal Sensation Scale
TTE  Time to Exhaustion
TWI  Temperate-Water Immersion
USG  Urine Specific Gravity
VA  Voluntary Activation
VCO_2  Carbon Dioxide Production
V_E  Minute Ventilation
VL  Vastus Lateralis
VM  Vastus Medialis
VO_2  Oxygen Consumption
VO_2max  Maximal Oxygen Consumption
WB  Whole Body
WBGT  Wet Bulb Globe Temperature
WU  Warm-Up
Symbols and Units

<  Less Than
>  Greater Than
\leq  Less Than or Equal To
\geq  Greater Than or Equal To
↑  Increased
↓  Decreased
↔  No change
=  Equals
±  Plus or Minus
%  Percentage
°  Degrees
°C  Degrees Celsius
AU  Arbitrary Units
Cm  Centimetre
dL  Decilitre
H  Hour
Hz  Hertz
Kg  Kilogram
M  Metre
m²  Square Metre
mA  Milliamp
min  Minute
mL  Millilitre
mm  Millimetre
mmol  Millimole
nmol  Nanomole
ms  Millisecond
mV  Millivolt
Ng  Nanogram
Nm  Newton Metre
rpm  Revolutions Per Minute
S  Second
μL  Micro Litre
μs  Micro Second
W  Watt
Y  Year
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Abstract

This thesis examined the effects of practical mixed-method cooling interventions for protection and recovery of medium-fast bowling performance in the heat, particularly focusing on the dosage effects required to elicit an ergogenic response. The initial investigation examined the effects of pre-cooling volume on neuromuscular function and performance during self-paced intermittent-sprint exercise in the heat. Ten male, team-sport athletes completed four randomised trials involving an 85 min cricket-specific self-paced intermittent-sprint exercise protocol in 33°C and 33% relative humidity. Pre-cooling interventions were applied for 20 min pre-exercise and included a control (no cooling; CONT), head (H), head+hand (HH), and whole-body methods (WB). Measures of maximal voluntary contraction (MVC) force and voluntary activation (VA) were obtained pre- and post-intervention and mid- and post-exercise. Self-paced intermittent-sprint running performance, core temperature ($T_c$), skin temperature ($T_{sk}$), heart rate (HR), rating of perceived exertion (RPE) and a thermal sensation scale (TSS) were monitored throughout. Further, venous and capillary blood samples were analysed for metabolite, muscle damage and inflammatory markers. The results demonstrated WB pre-cooling increased hard running distances by 12% compared to CONT ($P < 0.05$), and 6 – 7% compared to HH ($P= 0.02$) and H ($P= 0.001$), respectively. Similarly, WB pre-cooling blunted HR, $T_c$, $T_{sk}$, RPE and TSS responses during exercise to the greatest extent. Collectively, these data may highlight a link between pre-cooling volume and subsequent exercise performance, as larger surface area coverage augmented subsequent free-paced exercise capacity, in conjunction with greater suppression of physiological load. Importantly, however, similar changes in post-exercise MVC force after pre-cooling, regardless of the greater self-paced exercise completed may
highlight the effects of reduced thermal strain in maintaining central nervous system (CNS) contributions to protect self-selected intermittent-sprint performance in the heat.

The second study examined the effects of mixed-method pre-cooling duration on performance and neuromuscular function of self-paced intermittent-sprint shuttle running in the heat. Eight male, team-sport athletes completed 2 x 35 min bouts of intermittent-sprint shuttle running separated by a 15 min recovery on three separate occasions (33°C and 34% relative humidity). Mixed-method pre-cooling trials included a CONT (no cooling), 10 min (COOL10), and 20 min durations (COOL20). Performance was assessed via sprint times, % decline and shuttle-running distance covered. Neuromuscular function was assessed according to MVC force, VA and evoked twitch properties pre- and post-intervention and mid- and post-exercise. Measures of thermoregulatory (T_c, T_sk, and sweat loss), cardiovascular (HR), metabolic (capillary metabolites), and perceptual strain (RPE and TSS) were monitored throughout. Further, indirect markers of muscle damage and inflammation were analysed in venous blood samples collected pre- and post-exercise. Self-paced shuttle running increased by 5% after COOL20 (P < 0.05), likely reflecting a higher maintenance in MVC force (P < 0.05; d > 0.80), despite no inter-trial differences in VA (P > 0.05). Both pre-cooling durations reduced T_c throughout exercise (P < 0.05), with dose-specific reductions in body heat storage and pre- to post-exercise sweat losses (P < 0.05; d > 0.80) reflecting the duration of the pre-cooling stimulus applied. Accordingly, while a longer pre-cooling duration lowered physiological demands under heat stress, the maintenance of self-paced intermittent-sprint exercise only after a 20 min pre-cooling intervention may point to a thermal threshold required to preserve neuromuscular responses and so performance in hot conditions.
The aforementioned findings were then applied in a third study, examining the physiological and performance effects of pre-cooling on medium-fast bowling in the heat. Ten, medium-fast bowlers completed two randomised trials involving either a 20 min mixed-method pre-cooling or control (no cooling) intervention before a 6-over bowling spell in 32°C and 64% relative humidity. Measures included bowling performance (ball speed, accuracy and run-up speeds), physical movement characteristics (global positioning system monitoring and counter-movement jump height), physiological (HR, \(T_c\), \(T_{sk}\), and sweat loss), biochemical (serum concentrations of damage, stress and inflammation) and perceptual variables (RPE, and TSS). Pre-cooling demonstrated limited effects on bowling performance, with no difference in ball speed \((P= 0.63; d= 0.09)\), accuracy \((P= 0.76; d= 0.14)\) and total run-up speed \((P= 0.66; d= 0.06)\) observed between conditions. Nevertheless, pre-cooling did increase 20 m sprint speed by 6% at Over 4 \((P= 0.03; d= 0.75)\). Similar to previous, mixed-method pre-cooling blunted physiological (HR, \(T_c\), \(T_{sk}\), and sweat losses) and perceptual responses to medium-fast bowling in the heat \((P= 0.01 – 0.04; d= 0.34 – 3.13)\). Thus, despite no change in bowling performance, pre-cooling did reduce the thermoregulatory strain associated with medium-fast bowling in hot conditions.

The fourth study examined the effects of post-exercise cooling on physiological responses and cerebral haemodynamics in neuromuscular recovery following intermittent-sprint exercise in the heat. Nine male, team-sport athletes underwent three recovery trials including a control (CONT), mixed-method cooling (MIX) and cold-water immersion (10°C; CWI) after 85 min of cricket-specific self-paced intermittent-sprint running in 32°C and 42% relative humidity. MVC force and central activation were assessed simultaneously with
cerebral oxygenation (near-infrared spectroscopy) pre- and post-exercise, post-intervention, 1h post- and 24h post-exercise. HR, Tc, Ts and serum markers of muscle damage (creatine kinase; CK), inflammation (C-reactive protein; CRP) and stress (testosterone and cortisol) were measured throughout. CWI improved MVC recovery 1 h post-exercise by 13% and 16% compared to MIX and CONT (P < 0.01), respectively, corresponding with higher central activation and dose-specific reductions in HR, Tc and Ts post-intervention (P < 0.05). However, somewhat counterintuitive to improved neuromuscular performance, CWI reduced cerebral oxygenation compared to MIX and CONT post-intervention (P < 0.01). While all thermoregulatory changes had dissipated 24 h post-exercise (P > 0.05), MVC force remained 16% higher in the CWI trial compared to CONT (P < 0.05), perhaps owing to a preserved contractile structure as reflected via a blunted CK response (P= 0.04). These data highlight an apparent disassociation between acute neuromuscular recovery and cerebral oxygenation after post-exercise cooling, though point to dose-specific reductions in thermal strain as being integral in the maintenance of MVC force.

Finally, the fifth investigation examined the physiological and performance effects of post-exercise cooling on recovery of medium-fast bowlers in the heat. Eight medium-fast bowlers completed two randomised trials, involving two sessions completed on consecutive days (Session 1: 10-overs and Session 2: 4-overs) in 31°C and 55% relative humidity. Recovery interventions were administered for 20 min (MIX vs. CONT) after Session 1. Measures included bowling performance (ball speed, accuracy, and run-up speeds), physical demands (global positioning system, and counter-movement jump), physiological (HR, Tc, Ts and sweat loss), biochemical (CK, and CRP) and perceptual variables (RPE, TSS, and muscle soreness). Similar to Study 4, MIX reduced Tc, Ts and TSS during the intervention (P=
0.001–0.05; d= 1.31–5.78) and attenuated CK (P= 0.04; d= 0.56) and muscle soreness 24 h post-exercise (P= 0.03; d= 2.05). However, higher ball speeds were observed after MIX in Session 2 (P= 0.001; d= 0.67), reducing declines in ball speed between sessions (P= 0.03; d= 1.80). Large effects indicated higher accuracy in Session 2 after cooling (P= 0.13; d= 0.93), but no changes were apparent between conditions in next-day run-up speed (P= 0.97; d= 0.01) or counter-movement jump performance (P= 0.30–0.90; d= 0.08–0.47). Accordingly, mixed-method cooling may alleviate high thermal demands following a 10-over spell, improving physiological and perceptual recovery to maintain medium-fast bowling performance on consecutive days in the heat.

Collectively, these findings demonstrate the benefits of pre- and/or post-exercise cooling in easing thermal strain, maintaining self-paced intermittent-sprint performance and improving neuromuscular and functional recovery in the heat. Favourable physiological and performance effects reflected a dose-specific response to the cooling applied, as larger pre-cooling volumes (WB > HH > H > CONT) applied for longer practical durations (COOL20 > COOL10 > CONT) were most effective in blunting heat gain, maintaining self-selected work rates and CNS drive. Similarly, the greatest gains in neuromuscular recovery were apparent in relation to the physiological perturbation achieved (CWI > MIX > CONT). Importantly, however, mixed-method cooling was demonstrated to lessen the physiological and perceptual demands of medium-fast bowling in the heat, further improving the maintenance of technical skill performance on consecutive days. Accordingly, while appreciating the dosage effects, mixed-method cooling can assist to eliminate practical and logistical constraints to aid in the protection and recovery of exercise- and environment-induced heat stress in medium-fast bowlers.
CHAPTER 1

Introduction
1.1 Overview

Excessive increase in the physiological and perceptual demands of exercise in the heat are widely acknowledged to reduce performance and increase the risk of thermal injury from heat stress (Cheung & Sleivert, 2004; Reilly et al., 2006; Wendt et al., 2007). Specifically, disproportionate discrepancies in the heat gain/loss ratio exacerbates endogenous thermal load (Wendt et al., 2007), evoking afferent and/or efferent signaling to down-regulate exercise intensity and so avoiding cellular catastrophe (Marino, 2004; Tucker, 2009). For athletes competing in warm-to-hot environments, increased physiological and perceptual strain may manifest in premature declines in voluntary exercise capacity and neuromotor performance relevant to sports-specific skill (Bergeron et al., 2012). Specifically, exercise- and environment-induced heat stress is of concern for cricketers, particularly medium-fast bowlers, who must tolerate elevated endogenous and exogenous thermal loads to maintain prolonged and repeated near-maximal efforts (Petersen et al., 2010b). Inability to tolerate such demands may result in a reduction in both physical and skill performance (Devlin et al., 2001) or conversely, the potential for exertional heat illness to occur (Driscoll et al., 2008; Finch & Boufous, 2008).

Depending on game format, elite medium-fast bowlers cover ~3800 – 4100 m h\(^{-1}\), incorporating repeated high-intensity bouts (n= 54 – 61 efforts h\(^{-1}\)) that are separated by extended periods of lower-intensity fielding activities (Petersen et al., 2010b). These physical demands and regular scheduling of competitive cricket events in hot and humid conditions likely exacerbates the cardiovascular (heart rate range of 75 – 85% of maximum), metabolic (lactate values 4 – 5 mmol L\(^{-1}\)) and thermoregulatory strain (core temperature 38.5 – 38.8°C) reported during cricket activities in thermoneutral conditions (Duffield et al., 2009a).
such, the combination of high body temperatures and unsustainable fluid losses experienced by cricketers under heat stress (Gore et al., 1993) seemingly compromises both health status (Driscoll et al., 2008; Finch & Boufous, 2008) and cricket-specific performance outcomes (Devlin et al., 2001). Consequently, strategies to reduce the thermal load may be of benefit in cricket (Petersen et al., 2010a). However, to date the applicability of these procedures as well as the mechanisms underpinning performance outcomes are not fully understood (Duffield, 2008).

Considerable laboratory evidence supports the use of whole- and/or part-body cooling for performance and recovery in thermally stressful conditions (Marino, 2002; Quod et al., 2006; Duffield, 2008). Increasing heat storage capacity via pre-cooling is proposed to enhance exercise performance by allowing the completion of a greater volume of work prior to attainment of a critical core temperature (Quod et al., 2006). Additionally, the therapeutic qualities of cooling for post-exercise recovery have long been used to attenuate inflammation, oedema and discomfort associated with exercise-induced muscle soreness (Wilcock et al., 2006; Leeder et al., 2011). Hastening the reduction of endogenous thermal loads with cooling after exercise may also improve acute recovery of voluntary force and activation (Morrison et al., 2004; Thomas et al., 2006). Nevertheless, integrated central and peripheral contributors to the protection and recovery of exercise performance in the heat using cooling techniques have rendered underlying mechanisms elusive. Further, little evidence exists to support whole- and part-body mixed-method cooling techniques in competitive sports settings or scenarios specific to cricket. Therefore, this thesis aims to examine the effects of practical mixed-method cooling interventions for the protection and recovery of medium-fast bowling performance in the heat.
1.2 Cooling for Exercise Performance

Exercise in high ambient temperatures increase rates of heat storage as the combined gradient differences between metabolic heat production and environmental conditions for dry heat transfer is reduced (Wendt et al., 2007). In attempting to alleviate thermally regulated declines in self-paced and intermittent-sprint performance (Tucker et al., 2004; Drust et al., 2005), pre-cooling aims to offset ensuing heat gain and increase exercise capacity in hot conditions (Marino, 2002). Various pre-cooling modes are reported to reduce thermal loads (skin and/or core temperature) before exercise, including whole-body (cold-water immersion, cold air, combined treatments) and part-body methods (ice-vests, ice-packs, towels, fans, cold fluids) (Quod et al., 2006; Ross et al., 2011). However, discrepancies in methods are noteworthy in that the volume, duration and techniques administered may influence ensuing physiological responses and performance outcomes (Quod et al., 2006; Duffield, 2008; Bogerd et al., 2010). Accordingly, the direct effect of the ‘dose’ of pre-cooling (duration or surface area coverage) remains to be investigated.

Original hypotheses highlight artificial increases in heat storage capacity after pre-cooling to reduce body fluid losses and concomitant reductions in stroke volume, blunting cardiovascular demands so to improve oxygen uptake and supply (Wegmann et al., 2012). While protecting these cardio-circulatory factors, pre-cooling may ease increasing skeletal muscle and cerebral metabolism, substrate depletion and continued increases in body temperature (Bergeron et al., 2012). Concurrently, an improved thermoregulatory control could protect central nervous system (CNS) drive (Nybo & Nielsen, 2001a), possibly explaining the maintenance in neuromuscular recruitment and intermittent-sprint performance otherwise reduced during exercise in the heat (Skein et al., 2012). Accordingly, although pre-
cooling has not been examined in cricket-specific environments, it is possible that an enhanced thermal tolerance could improve medium-fast bowling performance and delay any protective feed-forward/feedback decline in exercise intensity (Marino, 2004; Tucker, 2004).

Regardless of specific mechanisms, pre-cooling may be advisable in hot conditions and could minimise premature declines in muscular contractile force and skill-specific neuromotor control (Bergeron et al., 2012). The negative impact of high environmental temperatures on medium-fast bowlers is pronounced, yet pre-cooling may assist cricketers to avoid previously reported involuntary dehydration (Gore et al., 1993), reduced bowling accuracy (Devlin et al., 2001) and heat-related illness (Driscoll et al., 2008; Finch & Boufous, 2008). Given the high bowling demands and extended match-play durations (up to 6 h day\(^{-1}\) across 4 – 5 days), pre-cooling may be particularly effective in reducing the thermoregulatory demands and enhancing performance of medium-fast bowlers in first-class cricket. Further, previously observed improvements in thermal tolerance and intermittent-sprint capacity after pre-cooling (Duffield & Marino, 2007) could protect a cricketer’s performance, particularly at the elite level where travel and scheduling can limit acclimatisation to local conditions before competition commencement (Petersen et al., 2010a).

1.3 Cooling for Recovery

Compounding the reduction in exercise capacity, greater physiological strain incurred during exercise such as medium-fast bowling in hot conditions likely slows recovery (Wendt et al., 2007), decreasing performance during subsequent exercise bouts (Duffield et al., 2009c). Nevertheless, cold-water immersion following exercise rapidly lowers high body
temperatures, improving physiological recovery and maintaining ensuing exercise performance in the heat (Peiffer et al., 2008; Vaile et al., 2008). Although the benefits of post-exercise cooling on perceived soreness and fatigue are commonly reported (Wilcock et al., 2006; Leeder et al., 2011), influences on performance or markers of muscle damage and inflammation vary (Bailey et al., 2007; Rowsell et al., 2009; Pournot et al., 2011). These discrepancies in recovery responses may be explained by different intervention durations, environmental conditions and subsequent performance assessments. Further, limited data from competitive scenarios also restricts current understanding of how cooling may affect sports-specific outcomes, such as medium-fast bowling on consecutive days.

Similar to the proposed cardio-dynamic factors associated with pre-cooling, lowering body temperature following exercise is reported to redirect blood flow to central organs, improving venous return and so reducing heart rate (Šrámek et al., 2000). While post-exercise cooling ameliorates cardiovascular strain, peripheral vasoconstriction decreases muscle blood flow (Vaile et al., 2011), lessening intracellular-intravascular fluid movements and associated oedema (Eston & Peters, 1999). Concurrently, however, just as post-exercise cooling may attenuate inflammation and perceptual soreness (Wilcock et al., 2006; Leeder et al., 2011) to maintain force production below the neuromuscular junction (Smith, 1990), lower core temperature may also alleviate thermally inhibited CNS drive (Morrison et al., 2004). Nevertheless, time-course differences in the expression of inflammatory events (24 – 72 h) and the recovery of neuromuscular outputs are not well understood (Pointon et al., 2012), and complicate recommendations of best practice for cricket-specific recovery in the heat.
Repeated high-force eccentric contractions incurred during medium-fast bowling disturb skeletal muscle function and evoke marked muscle damage responses (Noakes & Durandt, 2000). In hot conditions, peripheral recovery is likely impeded by exertional heat stress as ineffective heat loss mechanisms further exacerbate physiological demands, slowing recovery to potentially compromise a bowler’s physical capacities and/or neuromotor performance (e.g. ball speed and accuracy) (Petersen et al., 2010a). Considering the multiple and prolonged spells often required of medium-fast bowlers on consecutive days (Orchard et al., 2009), post-exercise cooling can assist to minimise compounding thermal strain and optimise physiological and perceptual recovery before ensuing medium-fast bowling performance. Even so, cold-water immersion techniques demonstrated in laboratory settings are not always feasible for cricketers and alternate methods to avoid infrastructural reliance (e.g. ice baths) and environmental concerns (e.g. water quality and quantity in the Sub-continental regions) need to be addressed.

1.4 Summary

Exercise- and environment-induced heat stress markedly increases the physiological and perceptual strain associated with exercise, invoking a CNS mediated reduction in exercise intensity, and an earlier and more prevalent manifestation of fatigue (González-Alonzo et al., 1999; Cheung & Sleivert, 2004; Duffield, 2008; Vaile et al., 2008). For cricketers, where exercise in the heat is often unavoidable, cooling interventions may delay or prevent the onset of excessive heat strain to maintain high-intensity performance or improve post-session recovery (Marino, 2002; Quod et al., 2006). Cold-water immersion is most conclusively supported for the protection and recovery of exercise performance (Duffield, 2008), yet is limited in the environmental and logistical practicality of field-based use by medium-fast
bowlers. Mixed-method approaches using multiple part-body techniques like ice-vests, ice-packs and cold towels could improve the practicality of cooling strategies (Barwood et al., 2009; Duffield et al., 2009d), with varied cooling doses potentially providing further insight into central and peripheral mechanisms regulating the reported ergogenic benefits. Greater maintenance of a thermal equilibrium through the administration of cooling strategies before and/or after medium-fast bowling in the heat is of relevance to cricketers and may ease physiological and perceptual demands underlying both performance and recovery.

1.5 Statement of the Problem

The location and seasonal scheduling of elite cricket competitions are frequently conducted in thermally stressful environments typical of the hot and humid conditions experienced in Africa, the Asian Sub-continent, Australia, the Middle East, and the West Indies. Subsequently, endogenous thermal loads are exacerbated by increasing metabolic heat production associated with exercise and compromised environmental heat loss, increasing physiological (heart rate, core temperature, skin temperature and oxygen consumption) and perceptual demands (perceived exertion and thermal stress) and decreasing exercise performance (Cheung & Sleivert, 2004; Reilly et al., 2006; Wendt et al., 2007). Pre- and post-exercise cooling strategies may assist to prevent or alleviate the effects of exercise- and environment-induced heat stress as reduced body temperatures assist to maintain health (Driscoll et al., 2008; Finch & Boufous, 2008) and medium-fast bowling performance (Devlin et al., 2001). Despite physiological and performance based interest in whole- and part-body cooling interventions, the underlying mechanisms are unclear. Further, the use of laboratory based research with whole-body cold-water immersion strategies reduces practicality for cricketers in ‘real world’ scenarios. Accordingly, literature is scarce
concerning practical mixed-method techniques in comparison with whole-body cold-water immersion. While recent research reports performance improvements for exercise in the heat following pre- and post-exercise cooling interventions (Duffield, 2008; Leeder et al., 2011), no evidence exists to demonstrate the physiological and performance implications of cooling interventions for cricket. Finally, a paucity of investigations incorporate sports-specific skills in addition to physiological and performance responses in the research methodology to provide a holistic understanding of cooling on performance and recovery of exercise in the heat.

1.6 Research Aims and Hypotheses

This thesis is comprised of five studies examining the physiological, neuromuscular and perceptual aspects of practical mixed-method cooling for the protection and recovery of cricket specific exercise performance in the heat. More specifically, this thesis aimed to examine the dosage effects of mixed-method cooling to develop parameters for field-based use that may benefit medium-fast bowlers within the constraints of competition or training location and demands.

**Study 1 – Pre-cooling Volume**

Research aims:

1. This study aimed to examine the effects of (mixed-method) pre-cooling volume on self-paced intermittent-sprint performance and physiological responses in the heat; and
2. To determine the effects of (mixed-method) pre-cooling volume on voluntary force and evoked twitch properties and their relationship to intermittent-sprint exercise performance in the heat.

Hypotheses:

1. It was hypothesised that a larger pre-cooling volume would improve self-paced intermittent-sprint performance through greater reductions in physiological demands; and

2. Greater reductions in pre-exercise body temperature achieved with larger pre-cooling volume would maintain voluntary force and activation during exercise in hot conditions.

**Study 2 – Pre-cooling Duration**

Research aims:

1. This study aimed to examine the effects of (mixed-method) pre-cooling duration on self-paced intermittent-sprint performance and physiological responses in the heat; and

2. To examine the effects of (mixed-method) pre-cooling duration on voluntary force and evoked twitch properties and their relationship to exercise performance in the heat.
Hypotheses:

1. It was hypothesised that a longer pre-cooling duration would improve self-paced intermittent-sprint performance through greater reductions in physiological demands; and

2. The larger reductions in thermal load achieved with a longer pre-cooling exposure would maintain voluntary force and activation during exercise in hot conditions.

Study 3 – Pre-Cooling for Medium-Fast Bowling Performance

Research aims:

1. This study aimed to determine physiological, perceptual and performance effects of mixed-method pre-cooling on a 6-over spell of medium-fast bowling in the heat.

Hypotheses:

1. It was hypothesised that mixed-method pre-cooling would improve performance and reduce the physiological demand of medium-fast bowling in the heat.

Study 4 – Post-Exercise Cooling Modalities

Research aims:

1. This study aimed to examine the effects of post-exercise cooling interventions on physiological, neuromuscular and perceptual recovery following intermittent-sprint exercise in the heat; particularly on cerebral oxygenation and subsequent neuromuscular function; and
2. To compare the effects of practical mixed-method cooling techniques with whole-body cold water immersion.

Hypotheses:

1. It was hypothesised that cold-water immersion would result in the maintenance of greater muscle recruitment and voluntary force compared to mixed-method cooling and control conditions, respectively; and

2. Whole-body cold-water immersion would demonstrate greater benefit to the recovery of voluntary and evoked neuromuscular force than mixed-method cooling and control conditions, respectively.

*Study 5 – Post-Exercise Cooling for the Recovery of Medium-Fast Bowling Performance*

Research aims:

1. This study aimed to examine physiological, perceptual and performance effects of post-exercise mixed-method cooling on recovery after a 10-over medium-fast bowling spell in the heat.

Hypotheses:

1. It was hypothesised that mixed-method cooling would hasten the recovery of physiological variables and medium-fast bowling performance in hot conditions.
1.7 Limitations

- A participant cohort of moderate – well trained male team sport athletes aged 18 - 25 years in Studies 1, 2 and 4 may restrict results being extrapolated to interpret the cricket specific findings of Studies 3 and 5. Further, these participant cohorts may not accurately reflect the effects of cooling on other populations.

- Assessments of isometric MVC are measured in Studies 1, 2 and 4 as an indicator of neuromuscular function. An isometric MVC of the right knee extensors may not accurately reflect the requirements of dynamic movements specific to medium-fast bowling.

- Measures of neuromuscular function were unable to be collected during the self-paced, intermittent-sprint exercise protocol (Studies 1, 2, and 4). Accordingly, these data may only indicate the effects of cooling and/or exercise on neuromuscular properties before, during and after exercise in the heat.

- Muscle mass, subcutaneous fat and skin thickness may impede electrical stimulation and the efficacy of cooling interventions during measures of evoked contractions.

- Participants were required to record dietary intake and physical activity, replicating the 24 h prior to each testing session. Although these were monitored throughout, total compliance is difficult to control.

- Data collection during Studies 2 and 4 was conducted in field-based settings and involve medium fast bowlers from the Cricket Australia Centre of Excellence. This setting prevents total control of all external variables and may restrict some measures.
1.8 Delimitations

- The isometric MVC protocols utilised in Studies 1, 2 and 4 facilitates the assessment of cooling on both central and peripheral contributors of voluntary force and activation, electromyography and evoked twitch properties. While an isometric MVC protocol may not reflect the movement demands of dynamic intermittent-sprint exercise, it does provide a measurement of contractile function at a given time point that would likely interrelate.

- Participants were requested to avoid the consumption of food and caffeine 3 h prior and alcohol 24 h prior to each testing session.

- Participants were requested to avoid strenuous exercise 24 h prior to testing.

- Data collection throughout Studies 1 and 3 were conducted in a controlled laboratory environment.

- Data collection times were standardised throughout to avoid diurnal variances.
CHAPTER 2

Literature Review
2.1 Overview

The detrimental effects of exercise- and environment-induced heat stress are of concern for the performance and recovery of physical capacity (Duffield, 2008), technical skill (Devlin et al., 2001) and heat-related injury in medium-fast bowlers (Driscoll et al., 2008; Finch & Boufous, 2008). While the repeated, high-intensity demands of medium-fast bowling contributes to increased exercise-induced heat production (Petersen et al., 2010b), the scheduling of major tournaments in hot conditions may exacerbate additional increases in endogenous body temperature as thermal control is reduced (Wendt et al., 2007). Administering cooling interventions before and/or after medium-fast bowling is likely to ameliorate the physiological demands of exercise in the heat to maintain performance and hasten optimal recovery (Duffield, 2008; Ranalli et al., 2010; Wegmann et al., 2012). However, questions relating to underlying mechanisms and the implementation of cold-water immersion in applied settings require further development, as an understanding of the dosage effects of cooling strategies is required so that practical alternatives may be utilised.

2.2 Literature Review Concept Tree

The review of literature aims to present a clear interpretation of the practical outcomes and underlying mechanisms of cooling for the protection and recovery of exercise-and environment-induced heat stress in medium-fast bowlers. Presumably, it is the physiological, neuromuscular and perceptual responses to pre- and/or post-exercise cooling that facilitates enhanced performance or hastened recovery after exercise in the heat. The concept tree (Figure 2.2) has been included to provide a visual overview of the themes relating to medium-fast bowling performance, exercise in the heat, the use of cooling strategies and how they may be applied as discussed in this literature review.
Figure 2.2: Conceptual overview of the review of literature.

Cooling for the protection and recovery of exercise- and environment-induced heat stress in medium-fast bowlers

- Medium-fast bowling
  - Physical demand and activity patterns
  - Physiological and perceptual demands
  - Development of fatigue
- Exercise in the heat
  - Self-paced exercise
  - Intermittent-sprint exercise
- Pre-cooling for exercise performance
  - Self-paced exercise
  - Intermittent-sprint exercise
  - Skill performance
- Post-exercise cooling for recovery
  - Self-paced exercise
  - Intermittent-sprint exercise
  - Skill performance
- Cooling methodology
  - Cold-water immersion
  - Field-based application

Mechanisms
- Physiological
  - Neuromuscular
  - Perceptual
- Physiological
  - Neuromuscular
  - Perceptual
2.3 Medium-Fast Bowling

Traditionally a recreation of Britain and its colonies, the bat-and-ball sport, cricket, is now recognised by the International Cricket Council in 105 member countries (International Cricket Council, 2011). Unlike other team sports, cricket matches may last up to five days, with constantly changing conditions (tactical, pitch surface, ball quality and weather patterns) contributing to performance and ultimately success. Cricket involves two teams of 11 players, with the aim of scoring a total of runs in excess of those scored by the opposition. Accordingly, batsmen hit the ball into the field and seek to make their ground by moving (running) from end-to-end of the pitch while the ball is in play to score a run (Figure 2.3.3). Alternatively, bowlers intend to restrict the batsman’s ability to score by delivering the ball so to dismiss the batsman, as bowled, caught, stumped, or leg before wicket (Marylebone Cricket Club, 2010). Intuitively then, a bowler’s ability to maximise and maintain ball speed, may increase competitive success (Wormgoor et al., 2010), as the available time for appropriate shot selection and execution of the batsman in reduced (Bartlett et al., 1996).

Despite this world-wide popularity, examination of the physiological demands of cricket have been traditionally limited; likely due to the largely conservative and complex social and political contexts in which the sport is played (Noakes & Durandt, 2000; Woolmer et al., 2008). Consequently, the unique physical characteristics of cricket are commonly perceived as undemanding, especially where repeated high-intensity efforts separated by extended periods of lower intensity activity contrast the activity profiles of other self-paced intermittent-sprint team sports (Noakes & Durandt, 2000). This interpretation, however, is somewhat misleading, particularly with respect to medium-fast bowlers training and/or competing in hot conditions (Gore et al., 1993; Devlin et al., 2001).
Figure 2.3: Schematic representation of a) common playing positions on a cricket field, and b) standardised dimensions of a cricket pitch in accordance with the Marylebone Cricket Club (2010).

1 = first slip; 2 = second slip; 3 = third slip; 4 = fourth slip; B = batsman; N = non-striker; U = umpire.
2.3.1 Physical Demands and Activity Patterns during Medium-Fast Bowling

Management of the physical and physiological state of high-performance athletes requires detailed understanding of training and competition demands. Despite considerable interest in the predictors and prevalence of cricket injuries, particularly in medium-fast bowlers (for detailed review see Finch et al., 1999; Stretch, 2007), limited time-motion analyses have, until recently, been conducted during either simulated or competitive cricket match-play (Duffield & Drinkwater, 2007). While this could be attributed to the labour-intensive nature of notational analyses and/or the duration of a cricket match (3 h – 5 days), recent advances in wearable global positioning system (GPS) technology have dramatically improved ease of access to these data (Petersen et al., 2009b). Accordingly, quantification of the movement requirements of cricketers highlight the physical efforts specific to playing position, format and competition level (Petersen et al., 2010b, 2011); further demonstrating the unique strain of cricket match-play previously dismissed as mild and relatively undemanding (Fletcher, 1955; Rudkin & O’Donogue, 2008).

Unique to cricket, elite players frequently compete interchangeably in three match formats (multi-day, one-day and Twenty20), each emphasising varied technical and tactical aptitudes for competitive success. Consequently, differences in movement patterns between match formats and playing position are noteworthy (Table 2.3.1; Table 2.3.2), with the total distance covered in a day’s play varying by as much as ~20.6 km (Petersen et al., 2010b, 2011). While these wide ranging physical demands present challenges in managing non-uniform workload and recovery requirements in the team setting, fast bowlers consistently demonstrate greater movement characteristics than other playing positions in all match formats (Petersen et al., 2010b). Petersen and colleagues (2010b) report national academy representative fast bowlers
to cover $5.5 \pm 0.4$ km (mean $\pm$ 90% confidence intervals), $13.4 \pm 0.7$ km, and $22.6 \pm 2.1$ km in total distance during Twenty20, one-day and multi-day matches, respectively. Comparatively, corresponding batsmen were reported to accumulate considerably lesser total distances during an entire Twenty20 ($3.5 \pm 0.2$ km), one-day ($8.7 \pm 0.6$ km) or multi-day innings ($13.0 \pm 2.0$ km). Further, it is possible that these discrepancies in player movement patterns could vary based on competition level (Petersen et al., 2011), perhaps indicative of the $\sim 2 - 3$ km higher total distances covered by fast bowlers during State Twenty20 (Petersen et al., 2009b) and International one-day matches (Petersen et al., 2009b).

The findings of Petersen et al. (2010b) further demonstrate the activity requirements of fast bowlers to be of a higher intensity than those reported of other playing positions in all match formats. Whilst not directly analysed, much of the additional movement requirements of fast bowlers would appear attributable to the markedly greater distances covered in striding ($4.01 - 5.00$ m s$^{-1}$) and sprinting ($\geq 5.01$ m s$^{-1}$) movement categories (Table 2.3.1; Petersen et al., 2009b, 2010b). Correspondingly, fast bowlers consistently completed a greater number of sprints ($\sim 7 - 21$ sprints h$^{-1}$) and high-intensity efforts ($\geq 3.51$ m s$^{-1}$; $\sim 16 - 49$ efforts h$^{-1}$) than other playing positions (Table 2.3.2; Petersen et al., 2010b, 2011). The intensity of movement demands also appear to be influenced by match format, particularly in fast bowlers, whereby Twenty20 players cover $\sim 90$ m h$^{-1}$ and $\sim 176$ m h$^{-1}$ greater distances at sprinting intensities than during one-day and multi-day cricket, respectively (Petersen et al., 2010b). Thus, although cumulative total distances in Twenty20 and one-day matches represent only 24 and 59% of those covered in multi-day cricket, relative intensities in terms of hourly sprint distance are inversely related to match duration in fast bowlers (Petersen et al., 2010b).
Regardless of match format, fast bowlers must tolerate a lower work-to-rest ratio when compared to the movement requirements of other playing positions (Table 2.3.2). In accounting for the higher number of sprints completed, Petersen et al. (2010b) report fast bowlers as the only position to engage in repeat-sprint activities (≥ 3 sprints with < 60 s recovery), likely associated with the number of overs bowled during each match. While these repeated high-intensity activities indicate greater physical demands required of a fast bowler (Petersen et al., 2009b, 2010b), they also contest common perception of the undemanding nature of cricket (Noakes & Durandt, 2000). In contrast, the 24 ± 7 sprints game⁻¹ endured by professional rugby union backs (Duthie et al., 2006) and sprint durations of 1.8 ± 0.4 s experienced in international men’s field hockey (Spencer et al., 2004) are comparably lower than those accommodated by fast bowlers during a Twenty20 innings of similar duration (80 min). These relative comparisons of intensity and work rate are reduced for longer match formats, though the similar intermittent nature and high eccentric loading point to the considerable metabolic strain incurred during fast bowling and should not be underestimated.
Table 2.3.1: Summary of studies examining the global positioning system movement category distances of cricketers.

<table>
<thead>
<tr>
<th>Study</th>
<th>Format</th>
<th>N</th>
<th>Competition</th>
<th>Intensity Walking (0-2.00 m/s&lt;sup&gt;1&lt;/sup&gt;)</th>
<th>Jogging (2.01-3.50 m/s&lt;sup&gt;1&lt;/sup&gt;)</th>
<th>Running (3.51-4.00 m/s&lt;sup&gt;1&lt;/sup&gt;)</th>
<th>Striding (4.01-5.00 m/s&lt;sup&gt;1&lt;/sup&gt;)</th>
<th>Sprinting (≥5.01 m/s&lt;sup&gt;1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast bowling</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)</td>
<td>Twenty20</td>
<td>26</td>
<td>Academy</td>
<td>2634 ± 268</td>
<td>718 ± 276</td>
<td>164 ± 76</td>
<td>249 ± 121</td>
<td>406 ± 230</td>
</tr>
<tr>
<td>Petersen et al. (2009a)</td>
<td>Twenty20</td>
<td>4</td>
<td>State</td>
<td>4288 ± 884</td>
<td>2195 ± 624</td>
<td>559 ± 184</td>
<td>725 ± 322</td>
<td>723 ± 168</td>
</tr>
<tr>
<td>Petersen et al. (2010b)</td>
<td>One-day</td>
<td>36</td>
<td>Academy</td>
<td>2520 ± 362</td>
<td>618 ± 217</td>
<td>157 ± 58</td>
<td>220 ± 81</td>
<td>316 ± 121</td>
</tr>
<tr>
<td>Petersen et al. (2011)</td>
<td>One-day</td>
<td>8</td>
<td>State</td>
<td>2626 ± 297</td>
<td>684 ± 158</td>
<td>154 ± 40</td>
<td>216 ± 47</td>
<td>344 ± 93</td>
</tr>
<tr>
<td>Petersen et al. (2009b)</td>
<td>One-day</td>
<td>12</td>
<td>International</td>
<td>10914 ± 2146</td>
<td>2490 ± 904</td>
<td>560 ± 145</td>
<td>798 ± 158</td>
<td>1140 ± 246</td>
</tr>
<tr>
<td>Petersen et al. (2011)</td>
<td>One-day</td>
<td>21</td>
<td>International</td>
<td>2936 ± 539</td>
<td>648 ± 220</td>
<td>145 ± 39</td>
<td>208 ± 53</td>
<td>341 ± 76</td>
</tr>
<tr>
<td>Petersen et al. (2010b)</td>
<td>Multi-day</td>
<td>9</td>
<td>Academy</td>
<td>2512 ± 258</td>
<td>614 ± 173</td>
<td>185 ± 89</td>
<td>233 ± 133</td>
<td>230 ± 149</td>
</tr>
<tr>
<td>Petersen et al. (2011)</td>
<td>First Class</td>
<td>80</td>
<td>State</td>
<td>2810 ± 487</td>
<td>574 ± 185</td>
<td>118 ± 42</td>
<td>187 ± 65</td>
<td>334 ± 134</td>
</tr>
<tr>
<td>Batting</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)</td>
<td>Twenty20</td>
<td>26</td>
<td>Academy</td>
<td>1638 ± 352</td>
<td>332 ± 103</td>
<td>97 ± 35</td>
<td>187 ± 70</td>
<td>175 ± 97</td>
</tr>
<tr>
<td>Petersen et al. (2009a)</td>
<td>Twenty20</td>
<td>4</td>
<td>State</td>
<td>1644 ± 507</td>
<td>395 ± 114</td>
<td>80 ± 34</td>
<td>153 ± 91</td>
<td>161 ± 83</td>
</tr>
<tr>
<td>Petersen et al. (2010b)</td>
<td>One-day</td>
<td>36</td>
<td>Academy</td>
<td>1808 ± 400</td>
<td>279 ± 119</td>
<td>86 ± 37</td>
<td>154 ± 70</td>
<td>149 ± 94</td>
</tr>
<tr>
<td>Petersen et al. (2010b)</td>
<td>Multi-day</td>
<td>9</td>
<td>Academy</td>
<td>1604 ± 438</td>
<td>200 ± 90</td>
<td>67 ± 18</td>
<td>107 ± 33</td>
<td>86 ± 28</td>
</tr>
<tr>
<td>Fielding</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)</td>
<td>Twenty20</td>
<td>26</td>
<td>Academy</td>
<td>2242 ± 448</td>
<td>737 ± 219</td>
<td>157 ± 71</td>
<td>182 ± 101</td>
<td>129 ± 91</td>
</tr>
<tr>
<td>Petersen et al. (2009a)</td>
<td>Twenty20</td>
<td>4</td>
<td>State</td>
<td>4381 ± 968</td>
<td>2042 ± 481</td>
<td>502 ± 208</td>
<td>215 ± 136</td>
<td>222 ± 55</td>
</tr>
<tr>
<td>Petersen et al. (2010b)</td>
<td>One-day</td>
<td>52</td>
<td>Academy</td>
<td>2117 ± 374</td>
<td>640 ± 193</td>
<td>119 ± 46</td>
<td>124 ± 59</td>
<td>81 ± 51</td>
</tr>
<tr>
<td>Petersen et al. (2011)</td>
<td>One-day</td>
<td>8</td>
<td>State</td>
<td>2388 ± 379</td>
<td>773 ± 171</td>
<td>159 ± 34</td>
<td>169 ± 42</td>
<td>138 ± 65</td>
</tr>
<tr>
<td>Petersen et al. (2010b)</td>
<td>Multi-day</td>
<td>20</td>
<td>Academy</td>
<td>1773 ± 339</td>
<td>480 ± 160</td>
<td>88 ± 43</td>
<td>83 ± 55</td>
<td>52 ± 33</td>
</tr>
<tr>
<td>Petersen et al. (2011)</td>
<td>First Class</td>
<td>80</td>
<td>State</td>
<td>2116 ± 562</td>
<td>520 ± 228</td>
<td>104 ± 48</td>
<td>117 ± 60</td>
<td>96 ± 64</td>
</tr>
</tbody>
</table>
Table 2.3.2: Summary of studies examining the global positioning system movement variables of cricketers.

<table>
<thead>
<tr>
<th>Study</th>
<th>Format</th>
<th>N</th>
<th>Competition</th>
<th>Number (#)</th>
<th>Mean Distance (m)</th>
<th>Max Speed (m(\text{s}^{-1}))</th>
<th>High-Intensity Efforts</th>
<th>Mean Effort Duration (s)</th>
<th>Recovery between (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fast bowling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)*</td>
<td>Twenty20</td>
<td>26</td>
<td>Academy</td>
<td>23 ± 10</td>
<td>17 ± 4</td>
<td>61 ± 25</td>
<td>25 ± 18*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2009a)‡</td>
<td>Twenty20</td>
<td>4</td>
<td>State</td>
<td>42 ± 8</td>
<td>17 ± 2</td>
<td>163 ± 44</td>
<td>2.6 ± 0.1</td>
<td>32 ± 10</td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)*</td>
<td>One-day</td>
<td>36</td>
<td>Academy</td>
<td>18 ± 5</td>
<td>18 ± 3</td>
<td>54 ± 14</td>
<td>25 ± 7*</td>
<td></td>
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</tr>
<tr>
<td>Petersen et al. (2011)*</td>
<td>One-day</td>
<td>8</td>
<td>State</td>
<td>20 ± 3</td>
<td>17 ± 3</td>
<td>53 ± 8</td>
<td>2.8 ± 0.2</td>
<td>69 ± 10</td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2009b)†</td>
<td>One-day</td>
<td>12</td>
<td>International</td>
<td>66 ± 11</td>
<td>18 ± 3</td>
<td>191 ± 32</td>
<td>2.7 ± 0.1</td>
<td>68 ± 12</td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2011)*</td>
<td>One-day</td>
<td>21</td>
<td>International</td>
<td>19 ± 4</td>
<td>18 ± 3</td>
<td>52 ± 11</td>
<td>2.8 ± 0.2</td>
<td>73 ± 21</td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)*</td>
<td>Multi-day</td>
<td>9</td>
<td>Academy</td>
<td>17 ± 11</td>
<td>13 ± 1</td>
<td>56 ± 29</td>
<td>38 ± 31*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2011)*</td>
<td>First Class</td>
<td>80</td>
<td>State</td>
<td>20 ± 7</td>
<td>17 ± 3</td>
<td>50 ± 22</td>
<td>2.7 ± 0.4</td>
<td>83 ± 35</td>
<td></td>
</tr>
<tr>
<td><strong>Batting</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)*</td>
<td>Twenty20</td>
<td>26</td>
<td>Academy</td>
<td>15 ± 9</td>
<td>13 ± 4</td>
<td>45 ± 16</td>
<td>38 ± 13*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2009a)‡</td>
<td>Twenty20</td>
<td>4</td>
<td>State</td>
<td>12 ± 5</td>
<td>14 ± 2</td>
<td>38 ± 17</td>
<td>2.2 ± 0.2</td>
<td>53 ± 24</td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)*</td>
<td>One-day</td>
<td>36</td>
<td>Academy</td>
<td>13 ± 9</td>
<td>11 ± 3</td>
<td>39 ± 16</td>
<td>50 ± 21*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)*</td>
<td>Multi-day</td>
<td>9</td>
<td>Academy</td>
<td>8 ± 3</td>
<td>13 ± 7</td>
<td>28 ± 6</td>
<td>61 ± 10*</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fielding</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)*</td>
<td>Twenty20</td>
<td>26</td>
<td>Academy</td>
<td>8 ± 5</td>
<td>15 ± 4</td>
<td>42 ± 20</td>
<td>43 ± 28*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2009a)‡</td>
<td>Twenty20</td>
<td>4</td>
<td>State</td>
<td>31 ± 18</td>
<td>17 ± 4</td>
<td>130 ± 57</td>
<td>2.8 ± 0.5</td>
<td>45 ± 21</td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)*</td>
<td>One-day</td>
<td>52</td>
<td>Academy</td>
<td>5 ± 3</td>
<td>15 ± 4</td>
<td>34 ± 14</td>
<td>62 ± 41*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2011)*</td>
<td>One-day</td>
<td>8</td>
<td>State</td>
<td>8 ± 4</td>
<td>15 ± 3</td>
<td>39 ± 9</td>
<td>2.8 ± 0.3</td>
<td>99 ± 28</td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2011)*</td>
<td>One-day</td>
<td>17</td>
<td>International</td>
<td>6 ± 4</td>
<td>15 ± 4</td>
<td>34 ± 17</td>
<td>2.6 ± 0.3</td>
<td>134 ± 73</td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2010b)*</td>
<td>Multi-day</td>
<td>20</td>
<td>Academy</td>
<td>3 ± 2</td>
<td>16 ± 7</td>
<td>19 ± 8</td>
<td>90 ± 52*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2011)*</td>
<td>First Class</td>
<td>80</td>
<td>State</td>
<td>5 ± 3</td>
<td>17 ± 6</td>
<td>26 ± 13</td>
<td>2.9 ± 0.6</td>
<td>188 ± 134</td>
<td></td>
</tr>
<tr>
<td>Petersen et al. (2011)*</td>
<td>Test Match</td>
<td>25</td>
<td>International</td>
<td>8 ± 4</td>
<td>18 ± 5</td>
<td>34 ± 11</td>
<td>3.1 ± 0.3</td>
<td>116 ± 37</td>
<td></td>
</tr>
</tbody>
</table>

\* scaled to 210 min
\‡ fielding innings scaled to 80 min; batting innings scaled to 30 min
\# scaled to 60 min
* work to rest ratio (1 : x).
2.3.2 Physiological and Perceptual Demands of Medium-Fast Bowling

Despite the long standing research into lower back injuries (Foster et al., 1989), and more recently time-motion characteristics (Petersen et al., 2009a, 2009b, 2010b); limited focus has been afforded to the physiological demands of medium-fast bowling. Indeed, following Fletcher’s (1955) estimations of energy expenditure during Test match (~1064 kJ h\(^{-1}\)) and net bowling (~1900 kJ h\(^{-1}\)), the physiological underpinnings of medium-fast bowling performance have been only sporadically examined in the last two decades (Noakes & Durandt, 2000; Christie, 2012). Various physiological, biochemical and perceptual responses to medium-fast bowling have been reported during competition (Gore et al., 1993; Soo & Naughton, 2007) or simulated training scenarios (Burnett et al., 1995; Stretch & Lambert, 1999; Devlin et al., 2001; Duffield et al., 2009a). However, considering the increasing competition scheduling and importance placed on physical fitness (Noakes & Durandt, 2000), limited and incomplete physiological and perceptual data underlying medium-fast bowling must be addressed to improve position-specific understanding of match demands.

Although current understanding of the physiological and perceptual requirements of medium-fast bowling are limited and incomplete (Johnstone & Ford, 2010), the collective integration of data may offer insight into task-representative demands. In generating ball speed, bowlers demonstrate high lower-body strength and rapid force development (Pyne et al., 2006) to optimise run-up speed leading into the delivery stride (Duffield et al., 2009a) and facilitate segmental acceleration through the bowling action (Glazier et al., 2000; Salter et al., 2007). Considering the need for these brief, near-maximal efforts to be repeated as many as 150 times a day in first-class cricket (Karppinen, 2010), albeit discontinuously, the anaerobic demands of this intermittent high-intensity exercise are presumably marked (Johnstone &
Interestingly however, the cardiovascular and metabolic strain of medium-fast bowling appears moderate, with mean heart rate responses of 155 – 180 beat min\(^{-1}\) (75 – 85% heart rate max) (Burnett et al., 1995; Devlin et al., 2001; Duffield et al., 2009a; Petersen et al., 2010b) and peak blood lactate concentrations of 4 – 5 mmol L\(^{-1}\) previously reported (Burnett et al., 1995; Duffield et al., 2009a). Accordingly, Noakes and Durandt (2000) highlight traditional cardiovascular-anaerobic, energy depletion and muscle power-muscle recruitment models of exercise performance as unable to explain match-related fatigue in cricket, instead offering a biomechanical model as a possible solution.

Medium-fast bowlers repetitively incur peak vertical and breaking forces ranging 3.8 – 9.0 and 1.4 – 3.5 times body weight, respectively, at front-foot impact during the delivery stride (Bartlett et al., 1996; Portus et al., 2004). Collectively, these high ground reaction forces and rapid segmental acceleration/deceleration through the leap, gather and follow-through impose substantial eccentric loading on medium-fast bowlers (Noakes & Durandt, 2000). Indeed, in an internal report for Cricket Australia, Brearley (2003) described elevated creatine kinase concentrations indicative of muscle damage in National Development Squad fast bowlers to peak at 811 ± 347 U L\(^{-1}\) following three successive days of competition. While the cumulative increases in perceptual soreness as reported by Duffield and others (2009a) could also be indicative of the muscle damage sustained by medium-fast bowlers, these authors observed no change in performance (ball speed and accuracy) or counter-movement jump height during or between repeated 6-over spells. The data of Brearley (2003) might indicate increasing disruption to muscle fibre structure to manifest in lowered neuromuscular power (~5% declines in vertical jump performance) after three days of consecutive match-play; however, given the low statistical power (n= 3) and absence of peer review, conclusions drawn from these data are limited. Accordingly, if and/or how muscle damage sustained
during medium-fast bowling may affect neuromuscular demands is unclear and warrants further investigation.

It is suggested that the physiological and perceptual demands of medium-fast bowling could be exacerbated by environmental heat stress, commonly experienced in Africa, the Asian Sub-continent, Australia, the Middle East and the West Indies (Noakes & Durandt, 2000). In fact, heat-related hospitalisation of Australian cricketers (n= 16) have been reported as higher than marathon runners (n= 10), and second only to lawn bowls (n= 20) (Driscoll et al., 2008). Nevertheless, these hospital separations cannot be explained by body temperatures alone, as rising $T_c$ at a rate of approximately 0.2°C per over to 38.8 ± 0.3°C during a 2 x 6-over spell (Duffield et al., 2009a) remain well below clinical classifications of heat illness (Howe & Boden, 2007). Although the data of Duffield and colleagues (2009a) was collected in mild temperatures (~21 – 23°C), larger relative contributions of metabolic load compared with environmental heat gain suggest the physical demands of medium-fast bowlers are unlikely to result in heat injury (Noakes & Durandt, 2000). Instead, high sweat rates and so lowered hydration status observed in cricketers (Gore et al., 1993; Soo & Naughton, 2007) may compound elevated body temperatures and could present as a key precursor to fatigue and heat exhaustion (Howe & Boden, 2007).

Gore et al. (1993) highlight profuse sweating and large body fluid deficits experienced by cricketers during both simulated and actual match play. Sweat rates reflected increasing environmental temperatures, with highest sweat losses observed in hot (1.37 ± 0.06 kg·h$^{-1}$), compared to warm (0.70 ± 0.03 kg·h$^{-1}$) and cool climates (0.54 ± 0.03 kg·h$^{-1}$), respectively. Further, sweat rates reported in fast bowlers during the initial 2 h session of match play in the
heat (1.67 ± 0.08 kg·h⁻¹) are comparable with singles tennis (Morante & Brotherhood, 2007), soccer training (Shirreffs et al., 2005) and marathon running in similar conditions (Noakes, 2012b). Perhaps most importantly, even with the availability of fluid replacement, fast bowlers appear unable to maintain hydration status in the heat, demonstrating progressive reductions in mean body mass as play continued (Session 1: -3.8 ± 0.5%; Session 2: -4.3 ± 0.7%) (Gore et al., 1993). Accordingly, despite the moderate increases in internal body temperatures in warm (Gore et al., 1993) and thermoneutral conditions (Duffield et al., 2009a), marked disturbances in fluid-balance could compromise medium-fast bowling performance (Devlin et al., 2001) and in extreme cases risk heat- or dehydration-related injury (Driscoll et al., 2008; Finch & Boufous, 2008).

2.3.3 Physical and Physiological Demands and the Development of Fatigue in Medium-Fast Bowlers

Medium-fast bowlers appear largely capable of maintaining both physical and skill performance during repeated (Duffield et al., 2009a) and extended bowling spells of up to 12 overs (Burnett et al., 1995; Portus et al., 2000). Remarkably, the maintenance of ball speed has been demonstrated under simulated conditions in senior club (Portus et al., 2000), state-development squad (Burnett et al., 1995) and first-class representative bowlers (Duffield et al., 2009a). Similarly, although bowling accuracy scores, as judged in relation to proximity to a designated grid-based target, have been shown to be more variable than ball speed, changes in mean accuracy were not significant in 8-over (Portus et al., 2000) or repeated 6-over spells (Duffield et al., 2009a). Considering the participant awareness of skill assessment in net-based scenarios, it is noteworthy that Duffield and colleagues (2009a) report trivial associations between ball speed and accuracy (r= 0.05), perhaps demonstrating the absence of
any conscious regulation of a speed/accuracy trade-off. Even so, any decline in physical capacity might be compensated by technique adjustments such as higher shoulder counter-rotation, possibly influencing bowling accuracy (Portus et al., 2000). Still, medium-fast bowlers seem able to accommodate the physiological demands of an extended spell (up to 12 overs), yet their capacity to repeat these efforts on consecutive days as required in match situations has received little attention (Brearley, 2003).

Consistent with the maintenance of ball speed and accuracy, medium-fast bowlers are reported to uphold neuromuscular performance, horizontal velocity (Duffield et al., 2009a) and kinematic characteristics throughout the run-up and delivery stride during an extended spell (Burnett et al., 1995). Even during 2 x 6-over spells, medium-fast bowlers demonstrate remarkably consistent final 5 m run-up speeds (Spell 1: 22.8 ± 1.9 vs. Spell 2: 22.7 ± 2.1 km h\(^{-1}\)) (Duffield et al., 2009a). While this may reflect the highly ‘rhythmical’ nature of the bowling run-up (Woolmer et al., 2008), it could also point to the sustained skeletal muscle function required to maintain vertical jump heights (Pre-spell 1: 0.43 ± 0.06 vs. Post-spell 2: 0.43 ± 0.07 m) (Duffield et al., 2009a). Nevertheless, considering the relatively short ~6500 m total distance accumulated during the simulated bowling spell (77% completed at < 14 km h\(^{-1}\)) of Duffield and colleagues (2009a), it is perhaps unsurprising that no decline in physical performance was evident. Accordingly, the review of Noakes and Durandt (2000) concludes that the mild metabolic and cardiovascular perturbations associated with medium-fast bowling are unlikely limiting factors of cricket performance. However, this interpretation could be restricted by the cool temperatures and non-competitive scenarios in which they were conducted, markedly dissimilar to match-play and the decrements in bowling performance noted in this context.
While the relationship between hydration and exercise performance has been recently questioned (Noakes, 2012b), in extreme cases, body-fluid deficits may exacerbate thermoregulatory strain (Sawka, 1992), reducing cognitive function (Cian et al., 2000) and potentially compromise the tactical and technical performance of cricketers (Devlin et al., 2001). Evidently, Devlin et al. (2001) highlights moderate hypohydration (↓ 2.8% body mass) to reduce the accuracy of line (↓ 16.4%) and length (↓ 15.4%), despite similar ball release speeds in medium-fast bowlers. Lowered sport-specific skill performance after exercise- and environment-induced hypohydration is common in team sports (Baker et al., 2007; Edwards et al., 2007); however, sub-maximal peak heart rate responses (~153 – 158 beats min⁻¹) (Devlin et al., 2001) and mild Tc rises observed in similar thermoneutral conditions (~38.8°C) (Duffield et al., 2009a), question whether these performance decrements are underpinned by physiological factors alone. Instead, the negative psychological associations (conscious or otherwise) derived from a greater perceptual effort consistently reported by Devlin et al. (2001) throughout hypohydration trials could also contribute to a lowered skill performance (Edwards et al., 2007). Regardless, how any potential psycho-physiological regulation of sports performance may relate to medium-fast bowlers is unclear and requires further investigation.

Alternatively, Noakes and Durandt (2000) highlight the eccentric loading and muscle damage associated with the rapid segmental acceleration and deceleration through the medium-fast bowling action to disrupt skeletal muscle function and explain physiological factors affecting performance. Accordingly, they propose that the repeated eccentric contractions may reduce elastic energy return and thus stretch-shortening efficiency (Nicol et al., 1991), increasing the physical work required to produce the necessary torque for optimal momentum and ball speed. This hypothesis does rationalise the comparable strength characteristics of South
African international cricketers and rugby union athletes despite the obvious differences in match demands (Noakes & Durandt, 2000). Although the neuromuscular recruitment characteristics of medium-fast bowling is unknown, it is possible that substantial muscle strength could minimise contractile unit disruption, possibly allowing cricketers to tolerate high braking ground reaction forces, which have been associated with faster delivery speeds (Portus et al., 2004). Nevertheless, muscle damage incurred after a ~7-over bowling spell as inferred via creatine kinase concentrations in fast bowlers (~589 U·L⁻¹) (Brearley, 2003) is considerably lower than that of a rugby union match (1081 ± 159 U·L⁻¹) (Takarada et al., 2003). Of course, a major limitation here is the lack of peer-reviewed data examining the CK efflux kinetics and recovery profile of medium-fast bowlers. Hence, while it is possible that this biomechanical explanation may contribute to the development of fatigue in medium-fast bowlers, its interaction and combination with other physiological and perceptual factors has not been addressed.

2.4 Exercise in the Heat

Exercise in the heat is a challenge for cricketers, as near year-round scheduling of international (northern and southern hemisphere summers) and lucrative domestic tournaments (Indian Premier League) ensure training and match play is commonly conducted in thermally stressful environments. Accordingly, exercise- and environment-induced heat stress elicits a cascade of physiological responses; specifically related to peripheral vasodilatation and redirection of central blood flow to enhance heat losses at the skin (Krogstad et al., 1995; Cheuvront et al., 2004; Kellogg, 2006). Further, where the thermal gradient restricts environmental heat loss, evaporation, by means of perspiration, may dissipate up to 600 kcal·h⁻¹ (Buono & Sjoholm, 1988). While these thermoregulatory
mechanisms are essential for the maintenance of homeostasis (Howe & Bodin, 2007), increasing metabolic heat gain alongside reduced heat gradients experienced during exercise in hot conditions can exacerbate thermal tolerance and reduce physical performance (Wendt et al., 2007). While current understanding of the thermal demands of medium-fast bowling is limited (Gore et al., 1993; Devlin et al., 2001), hot conditions are of concern in team sports, particularly considering the declines observed in self-paced and intermittent-sprint performance compared to thermoneutral conditions (Maxwell et al., 1996; Kay et al., 2001).

### 2.4.1 Self-Paced Exercise Performance in the Heat

The maintenance of prolonged, repeated intermittent-sprint efforts are integral to medium-fast bowling performance (Petersen et al., 2010b); however, the regulation of self-paced exercise intensity in the heat should not be overlooked. Commonly positioned in the outfield between overs, medium-fast bowlers may be required to cover considerable self-paced distances when fielding the ball, backing up a misfield, or altering fielding role (i.e. change of position). While the concept of pacing has been both supported (Duffield et al., 2009b; Coutts et al., 2010) and refuted (Aughey, 2010) in Australian Rules football, manipulating physical loads to control $T_c$ within tolerable limits is likely to benefit exercise capacity of team-sport athletes in hot conditions (Mohr et al., 2012). Indeed, the adverse affects of ambient temperature on pacing is particularly evident in cycling time trial performance (Table 2.4.1). Tucker and colleagues (2006) highlight a larger reduction in power output in the heat (35°C) compared to normal (25°C) and cool conditions (15°C) during cycling time trials fixed at a Borg rating of perceived exertion of 16 (2.35 ± 0.73 vs. 1.63 ± 0.70 vs. 1.61 ± 0.80 W min$^{-1}$; $P < 0.05$). Considering inter-trial differences in heat storage were only observed during the initial 4 min of the time trial, Tucker et al. (2006) concluded that self-selected work rates may
be continuously manipulated to preserve thermal homeostasis and ensure excessive heat accrual is avoided. While an inverse relationship between elevated body temperatures and lowered self-paced exercise performance is well supported (Table 2.4.2), the declines in power output (6.5%) despite similar $T_{re}$ reported by Tatterson et al. (2000) could indicate the contribution of multiple physiological, neuromuscular and perceptual agents in the regulation of self-paced exercise in the heat.

The aforementioned discrepancies in the time-course relationship between heat storage rates and improved self-selected exercise intensity (Tucker et al., 2006) is further compounded by an apparent mismatch between the declines in self-paced exercise intensity and neuromuscular recruitment (Tucker et al., 2004). Although exercise- and environment-induced heat stress is widely accepted to reduce CNS drive and lower MVC force production (Nybo & Nielsen, 2001a; Morrison et al., 2004; Todd et al., 2005), suggested inferences of isolated, isometric muscle contractions to the contraction patterns evident during prolonged, self-paced exercise remains unclear (Périard et al., 2011c). In comparing cycling time trial performance in hot (35°C) and cool (15°C) conditions, Tucker et al. (2004) report reduced iEMG activity at 50% of trial completion, yet lower power output in the heat was only apparent during the final 20% of exercise duration. Such an occurrence might be partially explained by the relatively large standard deviations in power output, though still does not elucidate a lesser neuromuscular performance given comparable changes in all thermoregulatory, cardiovascular and perceptual measures. Similarly, despite a slower 40 km cycling time trial in a hot environment ($59.8 \pm 2.6 \text{ vs. } 64.3 \pm 2.7 \text{ min}$), Périard et al. (2011c) found no difference in the post-exercise decline in MVC force compared to cool temperatures. Hence, as the additional increases in $T_{re}$ (~0.8°C) did not exacerbate the loss of MVC force, the authors attribute similar losses in voluntary force and activation to be mainly...
of peripheral origin. Alternatively, the greater preservation of anaerobic energy reserves achieved by adopting a lower pacing strategy (Foster et al., 2004) could allow for a relative increase in motor unit recruitment (Tucker et al., 2004), thus offering a different explanation for post-exercise maintenance of neuromuscular function.

Although it is recognised that exercise- and environment-induced heat stress may influence the regulation of self-selected exercise intensities, consensus on the afferent and/or efferent signalling pathways of pacing strategies is currently debated (Abbiss & Laursen, 2008). Tucker and colleagues (2004) interpret apparent reductions in work output and skeletal muscle recruitment prior to marked increases in body temperature to represent an anticipatory reduction in self-selected exercise intensity so to protect thermal homeostasis. Evidently, given the thermal advantage of smaller body mass in lowering heat production (Marino et al., 2000), this may explain the differences in the running speeds of African and Caucasian runners (~1.5 km h\(^{-1}\)) in the heat (35°C) from the outset of an 8 km time trial (Marino et al., 2004). When coupled with the findings of Tucker et al. (2006), whereby power output was reduced to maintain a fixed RPE value (16), these changes in performance may relate to a conscious or otherwise anticipation of the end point of exercise. However, where deception of both ambient conditions and \(T_c\) is applied, a lower RPE appears to improve 30 min cycling time trial performance in hot conditions (31°C), possibly through divergent subconscious expectation and conscious perception of thermoregulatory and neuromuscular demands (Castle et al., 2012). Accordingly, pacing strategies are seemingly continually altered in the heat, as an integration of CNS feed-forward and/or afferent sensory feedback counter rising thermal and metabolic strain during exercise (Lambert et al., 2005; Noakes et al., 2005).
Table 2.4.1: Summary of studies examining the effects of environmental heat stress on self-paced exercise performance.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Temperature</th>
<th>Exercise Protocol</th>
<th>Performance Effects</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altareki et al. (2009)</td>
<td>9</td>
<td>13°C vs. 35°C</td>
<td>4 km cycling time trial</td>
<td>↓ time trial performance (1.9%)</td>
<td>↑ HR, T&lt;sub&gt;re&lt;/sub&gt;, T&lt;sub&gt;b&lt;/sub&gt;, T&lt;sub&gt;a&lt;/sub&gt; and thermal sensation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ mean speed and PO</td>
<td>↔ VO&lt;sub&gt;2&lt;/sub&gt;, RER, La&lt;sup&gt;-&lt;/sup&gt; and RPE</td>
</tr>
<tr>
<td>Castle et al. (2012)</td>
<td>7</td>
<td>22°C (CONT) vs. 31°C (HOT) vs. 31°C (DEC; 26°C and T&lt;sub&gt;c&lt;/sub&gt; = 0.3°C)</td>
<td>30 min cycling time trial</td>
<td>↓ time trial performance (1.9%)</td>
<td>↔ iEMG, Tre, body fluid loss, HR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ mean speed and PO</td>
<td>↑ T&lt;sub&gt;a&lt;/sub&gt; in HOT and DEC trials</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ PO in DEC than HOT</td>
<td>↑ RPE at 2 min of warm-up in HOT vs. CONT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ PO DEC and CONT</td>
<td>↑ RPE at 3 min of time trial HOT vs. DEC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ MVC force</td>
<td>↑ thermal sensation in HOT and DEC</td>
</tr>
<tr>
<td>Ely et al. (2010)</td>
<td>8</td>
<td>21°C vs. 40°C</td>
<td>30-min cycling preload at 50% VO&lt;sub&gt;2peak&lt;/sub&gt; followed by a 15 min cycling time trial</td>
<td>↓ time trial work completed</td>
<td>↑ HR</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ fluid loss, fluid intake</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T&lt;sub&gt;c&lt;/sub&gt; and T&lt;sub&gt;s&lt;/sub&gt;k data lost</td>
</tr>
<tr>
<td>Marino et al. (2004)</td>
<td>12</td>
<td>15°C vs. 35°C</td>
<td>30 min treadmill running at 70% VO&lt;sub&gt;2max&lt;/sub&gt; followed by an 8 km running time trial</td>
<td>↓ time trial performance</td>
<td>↑ T&lt;sub&gt;re&lt;/sub&gt;, T&lt;sub&gt;s&lt;/sub&gt;k, HR, RPE</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>Heat storage positively correlated with body mass at 35°C</td>
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<td></td>
<td>Rate of heat storage was negatively correlated with body mass</td>
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<td></td>
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<td></td>
<td>↑ T&lt;sub&gt;re&lt;/sub&gt;, T&lt;sub&gt;a&lt;/sub&gt;, HR, RER, PEP, NH&lt;sub&gt;4&lt;/sub&gt;&lt;sup&gt;-&lt;/sup&gt;, La&lt;sup&gt;-&lt;/sup&gt;</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>↔ VO&lt;sub&gt;2&lt;/sub&gt;</td>
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<tr>
<td>Marino et al. (2000)</td>
<td>16</td>
<td>15°C vs. 25°C vs. 35°C</td>
<td>30 min treadmill running at 70% VO&lt;sub&gt;2max&lt;/sub&gt; followed by an 8 km running time trial</td>
<td>↓ time trial performance</td>
<td>↑ T&lt;sub&gt;re&lt;/sub&gt;, T&lt;sub&gt;a&lt;/sub&gt;, HR, RPE</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Heat storage positively correlated with body mass at 35°C</td>
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<td></td>
<td></td>
<td></td>
<td>Rate of heat storage was negatively correlated with body mass</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>↑ T&lt;sub&gt;re&lt;/sub&gt;, T&lt;sub&gt;a&lt;/sub&gt;, HR, RER, PEP, NH&lt;sub&gt;4&lt;/sub&gt;&lt;sup&gt;-&lt;/sup&gt;, La&lt;sup&gt;-&lt;/sup&gt;</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>↔ VO&lt;sub&gt;2&lt;/sub&gt;</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>↑ T&lt;sub&gt;re&lt;/sub&gt;, T&lt;sub&gt;a&lt;/sub&gt;, HR and skin blood flow</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ SV, Q and MAP</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ final km peak VO2</td>
</tr>
<tr>
<td>Périard et al. (2011b)</td>
<td>8</td>
<td>20°C vs. 35°C</td>
<td>40 km cycling time trial</td>
<td>↓ time trial performance</td>
<td>↑ HR, T&lt;sub&gt;re&lt;/sub&gt;, SwR, fluid intake and RPE</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ % body mass changes</td>
</tr>
<tr>
<td>Périard et al. (2011c)</td>
<td>9</td>
<td>20°C vs. 35°C</td>
<td>40 km cycling time trial</td>
<td>↓ time trial performance</td>
<td>↑ HR, T&lt;sub&gt;re&lt;/sub&gt;, SwR, fluid intake and RPE</td>
</tr>
</tbody>
</table>
Table 2.4.1: Summary of studies examining the effects of environmental heat stress on self-paced exercise performance continued.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Temperature</th>
<th>Exercise Protocol</th>
<th>Performance Effects</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tatterson et al. (2000)</td>
<td>11</td>
<td>23°C vs. 32°C</td>
<td>30 min cycling time trial</td>
<td>↓ PO (6.5%)</td>
<td>↑ mean Tsk and SwR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ PO during last 10 min</td>
<td>↔ Tc</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ PO during initial 10 min</td>
<td>↑ La’ and ↓ pH during first and final 10min of exercise</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ Tc, HR, and RPE</td>
</tr>
<tr>
<td>Tucker et al. (2004)</td>
<td>10</td>
<td>15°C vs. 35°C</td>
<td>20 km cycling time trial</td>
<td>↓ PO in final stages of protocol</td>
<td>↔ Tc, HR, and RPE</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ iEMG early in the protocol of exercise</td>
<td></td>
</tr>
<tr>
<td>Tucker et al. (2006)</td>
<td>8</td>
<td>15°C vs. 25°C vs.</td>
<td>Cycling trial adjusting PO to maintain an RPE of 16</td>
<td>↓ PO Hot compared to Neutral and Cool conditions</td>
<td>↑ rate of heat storage in first 4 min due to ↑ Tsk</td>
</tr>
<tr>
<td></td>
<td></td>
<td>35°C</td>
<td></td>
<td></td>
<td>↔ Tc</td>
</tr>
</tbody>
</table>

↑ = increased; ↓ = reduced; ↔ = no change; DEC = deception; HR = heart rate; km = kilometre; iEMG = integrated electromyography; La’ = lactate; MAP = mean arterial pressure; NH₄⁺ = ammonium; pH = potential hydrogen; PO = power output; Q = cardiac output; RER = respiratory exchange ratio; RPE = reported perceived exertion; SV = stroke volume; SwR = sweat rate; Tc = core temperature; Tcs = oesophageal temperature; Tb = body temperature; Tsk = skin temperature; VO₂ = oxygen consumption.
2.4.2 Intermittent-Sprint Exercise Performance in the Heat

Excessively high body temperatures exacerbate the physiological demands of exercise in the heat, reducing performance via a complex interaction of central, peripheral, perceptual and anticipatory mechanisms (Cheung, 2007; Noakes, 2012a). Consequently, the relationship between an elevated $T_c$ and ensuing physical performance profiles in team sports receives continued interest so as to explain the physiological and performance responses of athletes competing in the hot conditions common during elite tournaments (Duffield et al., 2009b; Özgünen et al., 2010; Mohr et al., 2012). Indeed, peak $T_c$ during competitive football (soccer) matches reportedly range from 39.0 – 39.3°C in cool – thermo-neutral conditions (Mohr et al., 2004; Edwards & Clarke, 2006), considerably lower than those experienced in the heat (39.1 – 39.7°C) (Mohr et al., 2012; Özgünen et al., 2010). While these $T_c$ values are not catastrophic (Howe & Bodin, 2007), this increasing thermal strain likely reflects an association with the intensity of game movement patterns as observed in Australian Rules football (Duffield et al., 2009b). Accordingly, when coupled with peak $T_c$ occurrence and a lowered physical performance profile during the latter stages of team sport matches in the heat, athletes appear to alter pacing strategies to maintain thermal strain within tolerable limits (Duffield et al., 2009b). This may be further evidenced by the tactical approach adopted, as footballers utilise possession- rather than transition-oriented tactics to better control match speed in the heat (41% less high intensity running and ~25% more time in possession) (Mohr et al., 2012).

In contrast, laboratory-based exercise protocols highlight the exercise and duration specific influences of high thermal strain on intermittent-sprint performance (Duffield, 2008; Table 2.4.1). Accordingly, where three consecutive Wingate cycling tests are interspersed with low-
intensity recovery (work-to-rest ratio = 1:1), differences in environmental temperature and relative humidity demonstrate no adverse affects on power output or metabolic and cardiovascular loads (Backx et al., 2000a, b). In fact, high ambient temperatures may even increase mean and peak power output during repeated maximal cycling bouts (2 x 30 s bouts, 4 min recovery), perhaps attributable to effects of temperature on the force/velocity characteristics of slow twitch type I muscle fibres (Ball et al., 1999). Nevertheless, these performance gains were coupled with a faster fatigability under heat stress (Ball et al., 1999), increasingly evident as exercise duration is extended (Drust et al., 2005). Drust and colleagues (2005) highlighted greater declines in mean power output during a 40 min intermittent sprint cycling protocol in the heat (558.0 ± 146.9 vs. 617.5 ± 122.6 W; \(P < 0.05\)), particularly evident in the final four 15 s sprints. Notably, in spite of a lower oxygen uptake during the repeated sprints, concentrations of plasma catecholamines, muscle lactate and glycogen utilisation were similar in both hot (40°C) and thermo-neutral conditions (20°C). Collectively then, these data may point to the adverse affects of high \(T_c\) and not the accumulation of metabolic byproducts as fatigue agents during intermittent-sprint exercise (Ball et al., 1999; Morris et al., 2000; Morris et al., 2005).

Importantly, as demonstrated by the field-based GPS data of Duffield and others (2009b), very-high intensity efforts could be protected by reducing sub-maximal exercise intensities. Considering this, analyses of self-paced exercise completed between maximal efforts as experienced in team sports must be considered as a regulator of metabolic heat gain, and thus a body temperature control (Marino, 2004; Tucker et al., 2004). In attempting to address this, Morris and colleagues (2000) examined the effect of high ambient temperature on prolonged intermittent shuttle running (a modified 75 min Loughborough Intermittent Sprint Test) followed by repeated 60 s efforts at 100% VO\(_{2\text{max}}\) on a work-to-rest ratio of 1:1 until fatigue.
Most pertinent, significant correlations were reported for the relationship between the rate of rise in rectal temperature ($T_{re}$) and shuttle-running distances completed ($r = -0.93 - 0.94; P < 0.01$), albeit 4% less in 30°C compared to 16°C temperatures. Correspondingly, Maxwell and co-authors (2008) show a ~4% increase in peak power output where reduced active recovery intensity (35% vs. 50% VO$_{2\max}$) during intermittent-sprint cycling in hot conditions slows the rate of metabolic heat gain. It is likely then, that interplay between sub-maximal intensities and increases in $T_c$, even in the absence of any obvious peripheral alterations, may decrease intermittent-sprint capacity in the heat (Morris et al., 1998, 2005). An obvious limitation of this conclusion, however, is the fixed (Maxwell et al., 2008) and standardised exercise intensities completed (Morris et al., 1998, 2000, 2005) that do not accurately reflect the instinctive movement demands and self-paced nature of team sports.

Collectively, these studies highlight the impaired performance of prolonged intermittent-sprint and self-paced exercise under heat stress (Reilly et al., 2006). Much of the decline in voluntary exercise capacity has been attributed to an elevated $T_c$, as increasing metabolic heat gain is exacerbated by restricted heat transfer to the surrounding environment (Hargreaves, 2008). Consequently, high thermal loads and concomitant redistribution of cardiac supply to the periphery to facilitate a higher sweat rate reduces blood volume and is associated with a progressive cardiovascular drift and lowered VO$_{2\max}$ during prolonged exercise in the heat (Wingo & Cureton, 2006). While these adverse affects are largely alleviated in thermoneutral and cool conditions, team-sport athletes, especially cricketers, are rarely afforded the opportunity to train and/or play in these mild ambient conditions. Accordingly, where high temperatures are unavoidable, the use of cooling strategies applied before and/or after exercise may assist to ease unfavourable heat storage strain, lowering physiological demands to the benefit of performance and recovery (Duffield, 2008). The following section will
discuss pre- and post-exercise cooling for hot conditions and how this may protect, and aid recovery from, exercise- and environment-induced heat stress in medium-fast bowlers.
Table 2.4.2: Summary of studies examining the effects of environmental heat stress on intermittent-sprint exercise performance.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Temperature (relative humidity)</th>
<th>Exercise Protocol</th>
<th>Performance Effects</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball et al. (1999)</td>
<td>7</td>
<td>19°C vs. 30°C</td>
<td>2 x 30 s sprints on cycle ergometer (4 min passive recovery)</td>
<td>↑ Mean and PPO during both sprints Faster rate of fatigue</td>
<td>↔ La&lt;sup&gt;–&lt;/sup&gt;</td>
</tr>
<tr>
<td>Backx et al. (2000a)</td>
<td>8</td>
<td>22°C, 30% RH (N) vs. 30°C, 85% RH (WET) vs. 40°C, 40% RH (HOT)</td>
<td>3 x 30 s Wingate test (30 s recovery)</td>
<td>↔ PPO</td>
<td>↔ VO&lt;sub&gt;2&lt;/sub&gt;, VCO&lt;sub&gt;2&lt;/sub&gt;, haematocrit, pH, La&lt;sup&gt;–&lt;/sup&gt;, HR, osmolarity.</td>
</tr>
<tr>
<td>Backx et al. (2000b)</td>
<td>8</td>
<td>22°C, 30% RH (N) vs. 30°C, 85% RH (HOT) vs. 40°C, 40% RH (HOT)</td>
<td>3 x 30 s Wingate test (30 s recovery)</td>
<td>↔ Mean and PPO</td>
<td>↑ recovery HR in H</td>
</tr>
<tr>
<td>Falk et al. (1998)</td>
<td>11</td>
<td>22°C vs. 35°C</td>
<td>5 x 15 s cycling sprints (series 1) separated by 30 s active recovery and repeated 60 min later in hot or neutral conditions (series 2)</td>
<td>↑ PPO during series 1 ↔ PPO during series 2</td>
<td>↑ T&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>Drust et al. (2005)</td>
<td>7</td>
<td>20°C vs. 40°C</td>
<td>40 min intermittent-sprint protocol on cycle ergometer followed by 5 x 15 s sprint (15 s recovery)</td>
<td>↔ PO during sprint 1 ↓ PO during sprint 2-5</td>
<td>↑ T&lt;sub&gt;c&lt;/sub&gt;, T&lt;sub&gt;mu&lt;/sub&gt;, HR, noradrenaline concentration ↑ RPE</td>
</tr>
<tr>
<td>Mohr et al. (2012)</td>
<td>17</td>
<td>21°C vs. 43°C</td>
<td>90 min football (soccer) game followed by 3 x 30 m sprint (25 s recovery)</td>
<td>↓ total distance, high-intensity distance, ↑ peak sprint speed ↔ total sprint distance and sprint frequency, post-game RSA ↑ passing success rate</td>
<td>↑ T&lt;sub&gt;c&lt;/sub&gt;, T&lt;sub&gt;mu&lt;/sub&gt;, SwR ↔ HR, La&lt;sup&gt;–&lt;/sup&gt;, Glu, Na&lt;sup&gt;+&lt;/sup&gt;</td>
</tr>
<tr>
<td>Morris et al. (1998)</td>
<td>12</td>
<td>20°C vs. 30°C</td>
<td>Part A: 75 min LIST Part B: 60 s runs at ~99% predicted VO&lt;sub&gt;2&lt;/sub&gt;max (60 s recovery) until fatigue</td>
<td>↓ distance covered ↔ 15 m sprint time</td>
<td>↑ T&lt;sub&gt;re&lt;/sub&gt;, HR, fluid intake ↔ body mass loss, RPE, Glu, La&lt;sup&gt;–&lt;/sup&gt;, NH&lt;sub&gt;3&lt;/sub&gt;, FFA</td>
</tr>
<tr>
<td>Morris et al. (2000)</td>
<td>16</td>
<td>16°C vs. 30°C</td>
<td>Part A: 75 min LIST Part B: 60 s runs at 100% predicted VO2max (60 s recovery) until fatigue</td>
<td>Part A: 25% less work completed Part B: Slower sprint times</td>
<td>↑ T&lt;sub&gt;c&lt;/sub&gt; ↔ La&lt;sup&gt;–&lt;/sup&gt; and NH&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
</tbody>
</table>
Table 2.4.2: Summary of studies examining the effects of environmental heat stress on intermittent-sprint exercise performance continued.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Temperature (relative humidity)</th>
<th>Exercise Protocol</th>
<th>Performance Effects</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morris et al. (2005)</td>
<td>9</td>
<td>17°C vs. 33°C</td>
<td>Part A: Modified LIST for 14.8 + 0.1 min followed by a 3 min rest, then continued exercise until exhaustion</td>
<td>↓ distance covered, ↑ sprint times, ↓ 2nd half total distance covered in HH, ↑ mean distance and % total distance walking in HH, ↓ % total distance completed low-moderate running</td>
<td>↑ HR, Tc, Tmu, La, Glu, catecholamines ↑ muscle glycogen utilisation ↑ Tc in HH by 35 min of 1st half ↔ 2nd half Tc ↑ HR in 1st half vs. 2nd half in both trials ↔ SwR</td>
</tr>
<tr>
<td>Özgünen et al. (2010)</td>
<td>11</td>
<td>34°C (MH) vs. 36°C (HH)</td>
<td>90 min football (soccer) game</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

↑ = increased; ↓ = reduced; ↔ = no change; FFA = free fatty acid; Glu = glucose; H = hot; HH = high heat; HR = heart rate; HU = humid; La = lactate; LIST = Loughborough Intermittent Shuttle Test; MH = moderate heat; N = normal; Na = sodium; NH3 = ammonia; PO = power output; RH = relative humidity; RPE = reported perceived exertion; RSA = repeat sprint ability; SwR = sweat rate; Tc = core temperature; Tmu = muscle temperature; Tre = rectal temperature; TTE = time to exhaustion; VCO2 = carbon dioxide production; VO2 = oxygen consumption.
2.5 Pre-Cooling for Exercise Performance in the Heat

Hot and humid conditions limit exercise performance as self-selected intensities are reduced to ease metabolic heat gain and maintain T_c within tolerable limits (Wendt et al., 2007). To counter this, pre-cooling techniques aim to reduce body temperatures before exercise, increasing heat storage reserves to delay the down-regulation of exercise intensity and/or the attainment of a critically limiting temperature and hyperthermic fatigue (Marino, 2002; Quod et al., 2006; Duffield, 2008). Generally, pre-cooling is demonstrated to improve time to exhaustion (Olschewski & Brück, 1988; Lee & Haymes, 1995) or self-paced distances covered (Booth et al., 1997; Kay et al., 1999). However, given the differences in methodology reported (e.g. pre-cooling volume, duration, technique, exercise protocols and environmental conditions), mechanisms underlying these performance gains and practical solutions to overcome issues surrounding implementation in the field remain elusive (Quod et al., 2006; Wegmann et al., 2012).

2.5.1 Pre-Cooling for Self-Paced Exercise Performance in the Heat

As depicted in Table 2.5.1, considerable evidence supports the use of pre-cooling during self-paced exercise, particularly for prolonged endurance bouts (Marino, 2002; Quod et al., 2006; Duffield, 2008). However, traditional experimental designs limit practical inferences as demonstrated improvements in work completed (Hessemer et al., 1984; Booth et al., 1997; Cotter et al., 2001) or time to exhaustion at a constant intensity (Schmidt & Brück, 1981; Olschewski & Brück, 1988; Lee & Haymes, 1995) are largely dissimilar to real-world competition. Importantly though, recently reported performance-based protocols offer greater insight into the manipulation of pacing strategies as an explanation for higher self-paced exercise performance in the heat (Quod et al., 2008; Duffield et al., 2010; Ross et al., 2011).
While self-paced exercise trials most commonly involve continuous cycling protocols, the manipulation of exercise intensities in relation to thermal strain during self-paced exercise may offer further insight into self-selected work rates integral to team-sport, and more specifically, medium-fast bowling performance.

Cotter and colleagues (2001) reported a 16 – 17.5% increase in mean power output during a self-paced performance trial, having reduced body temperature ($T_b$) by 2.8°C through the combined use of an ice-vest and cryogenic leg cuffs while seated in a 3°C cold room. Quod et al. (2008) similarly demonstrated pre-cooling to improve performance time by 42 s (1.8%) over a 20 min self-paced trial immediately after 20 min of fixed-intensity cycling at 75 ± 4.5% of mean aerobic power in 35°C heat. Importantly, performance trends appeared to relate to the level of reduction in thermal load, as the combined ice jacket-plunge pool (24°C) protocol lowered $T_{re}$ by 0.7°C compared to rest, and 0.5°C and 0.6°C cooler than ice jacket and control conditions, respectively (Quod et al., 2008). Although these data support the influence of a larger heat storage and lower thermal strain in improving self-paced exercise performance (Marino, 2002), the lowering of internal body temperatures may not always be necessary for this to occur. Accordingly, Kay et al. (1999) showed a lowering of $T_{sk}$ pre-exercise, without change in $T_c$ or heart rate, to enhance 30 min self-paced cycling performance in hot, humid conditions (31°C, 60% relative humidity), presumably owing to afferent inputs of thermal perception facilitating higher initial power output (Schlader et al., 2011). In contrast, however, Duffield et al. (2010) detailed higher power output during the final 10 min of a 40 min cycling time trial in 33°C heat, well after pre-cooling induced changes in physiological changes (apart from sweat losses) had dissipated. Collectively these data highlight pre-cooling to extend and/or maintain optimal pacing strategies in the heat, even though specific mechanisms remain equivocal.
Importantly for team sports, comparable trends have been replicated in running protocols. Booth and others (1997) examined cold-water immersion (23-24°C) to pre-cool before a 30 min self-paced treadmill running bout in the heat (32°C). Pre-cooling increased running performance by 304 ± 166 m (~4%); notably via increased self-selected speeds throughout the time trial, with an end-spurt prominent in the final 5 min split that was otherwise maintained during control conditions (Marino, 2002). These findings are further reflected in the data of Arngrímsson et al. (2004), who demonstrate ice vest use during an active warm-up in 32°C heat to enhance 5 km run time by ~13 s. Comparable to the results of Booth et al. (1997), the faster pacing strategies adopted in pre-cooling trials were most obvious during the final two-thirds of the protocol, even though blunted $T_e$, heart rate and thermal discomfort responses were eliminated in the initial 3.2 km. Hence, instead of improving performance per se, taken together these studies suggest that the lowered physiological demands of self-paced exercise after pre-cooling may allow access to muscle reserves and thus an end-spurt rather than merely maintenance of work rate (Marino, 2002).

While the use of pre-cooling techniques are widely supported in their benefit for self-paced intermittent-sprint performance in the heat, further consideration for sport-specific effects warrants attention (Wegmann et al., 2012). Indeed, Bolster and colleagues (1999) highlighted no physiological advantage to pre-cooling before a simulated duathalon (15 min swim and 45 min cycling) in 27°C ambient temperatures. Unfortunately, no performance based data were reported; however, the author’s concluded that although a standardised reduction in $T_{re}$ of 0.5°C was achieved using 26°C water immersion, increases heat storage capacity (109 ± 6 vs. 79 ± 4 W m$^{-2}$; $P < 0.05$) without other physiological change (VO$_2$, HR, and sweat rates) pre-cooling is not advisable for such events. Marino (2002) reasons that water immersion pre-cooling before swimming exercise in a similar environment could have masked potential
thermoregulatory benefits otherwise experienced in running or cycling modes. Further, it is pertinent that some participants reported being “stiff” and “sluggish” during the swim (Bolster et al., 1999), possibly indicating altered mechanical efficiency and/or power output experienced with a lowered $T_{mu}$ (Racinais & Oksa, 2010). Although the physiological rationale and absence of performance data render conclusions of ‘no effect’ premature (Bolster et al., 1999), these data do highlight the wider need for sports specific pre-cooling to be examined so to understand how different exercise modes may influence pre-cooling outcomes (Wegmann et al., 2012). This may be pertinent for the medium-fast bowler, particularly where the speed/accuracy trade-off during skill performance (Sachlikidis & Salter, 2007) might mask performance benefits of pre-cooling via a paced and controlled bowling action (Woolmer et al., 2008).
### Table 2.5.1: Summary of studies examining the effects of pre-cooling on self-paced exercise performance.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Temperature</th>
<th>Cooling Intervention</th>
<th>Exercise Protocol</th>
<th>Performance Effects</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arngrímsson et al. (2004)</td>
<td>17</td>
<td>32°C</td>
<td>38 min, ice-vest worn during warm-up</td>
<td>5 km treadmill running time trial</td>
<td>↑ time trial performance</td>
<td>↓ $T_{es}$, $T_{re}$, $T_{sk}$, $T_{b}$, HR, thermal discomfort</td>
</tr>
<tr>
<td>Booth et al. (1997)</td>
<td>8</td>
<td>32°C</td>
<td>60 min, whole-body CWI (23-24°C)</td>
<td>30 min treadmill running time trial</td>
<td>↑ time trial performance</td>
<td>↓ $T_{es}$, $T_{re}$, $T_{sk}$, HR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↑ $La^-$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ VO$_2$, sweat rate</td>
</tr>
<tr>
<td>Cotter et al. (2001)</td>
<td>9</td>
<td>34°C</td>
<td>45 min, ice-vest and cold air (3°C), with (LC) and without (LW) leg cooling vs. no cooling (CONT ; 34°C)</td>
<td>20 min at ~65% $VO_{2peak}$ followed by a 15 min work-performance trial</td>
<td>↑ PO in LC and LW vs. ↔ LC and LW</td>
<td>↓ $T_{es}$, $T_{sk}$, HR, forearm blood flow, RPE, thermal discomfort</td>
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<tr>
<td>Duffield et al. (2010)</td>
<td>8</td>
<td>33°C</td>
<td>20 min, lower-body CWI (14°C)</td>
<td>40 min cycling time trial</td>
<td>↑ time trial performance in final 10 min</td>
<td>↓ $T_{es}$, $T_{re}$, $T_{sk}$, $T_{b}$, until 20th min</td>
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<td></td>
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<td></td>
<td></td>
<td>↔ voluntary and evoked MVC force</td>
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<td></td>
<td></td>
<td></td>
<td>↓ TSS, pre-ex $La^-$</td>
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<td></td>
<td></td>
<td></td>
<td>↔ HR, Glu, RPE</td>
</tr>
<tr>
<td>Kay et al. (1999)</td>
<td>7</td>
<td>31°C</td>
<td>60 min whole-body water immersion (26°C)</td>
<td>30 min cycling time trial (~0.9 km)</td>
<td>↑ time trial performance</td>
<td>↓ $T_{sk}$, $T_{b}$, sweat rate</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ $T_{es}$ from 15-20th min</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↑ heat storage, VO$_2$</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ HR, $La^-$</td>
</tr>
</tbody>
</table>
Table 2.5.1: Summary of studies examining the effects of pre-cooling on self-paced exercise performance continued.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Temperature</th>
<th>Cooling Intervention</th>
<th>Exercise Protocol</th>
<th>Performance Effects</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quod et al. (2008)</td>
<td>6</td>
<td>34°C</td>
<td>40 min no cooling (34°C; CONT); 40 min ice jacket (jacket); 30 min water immersion (24°C) + 40 min ice jacket (combined)</td>
<td>40 min fixed-power/variable-power cycling time trial</td>
<td>↑ time trial performance in combined (-1.8%)</td>
<td>↓T&lt;sub&gt;re&lt;/sub&gt;, T&lt;sub&gt;sk&lt;/sub&gt;, T&lt;sub&gt;b&lt;/sub&gt;, HR in combined</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ time trial performance jacket and control</td>
<td>↓ thermal sensation in jacket and combined</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↑La⁻ in jacket</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ pH, Glu, HCO&lt;sub&gt;3&lt;/sub&gt;</td>
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</tr>
<tr>
<td>Ross et al. (2011)</td>
<td>11</td>
<td>32-35°C</td>
<td>30 min, no cooling ad libitum cold fluid intake (4°C; CONT); CWI (10°C, 10 min) + ice jacket (20 min; STD COOL); ice slushie + iced towels on torso and legs (30 min; NEW COOL)</td>
<td>Cycling time trial simulation of the Beijing Olympic Games course</td>
<td>↑ PO (3%) and ↓ performance time (1.3%) in NEW COOL vs. CONT</td>
<td>↓T&lt;sub&gt;re&lt;/sub&gt; pre-ex (STD COOL &lt; NEW COOL &lt; CONT)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ STD COOL vs. CONT</td>
<td>↔ T&lt;sub&gt;re&lt;/sub&gt;, HR, RPE</td>
</tr>
<tr>
<td>Siegel et al. (2012)</td>
<td>8</td>
<td>34°C</td>
<td>Ice slurry ingestion (ICE); CWI (24°C); warm fluid ingestion (CONT)</td>
<td>Treadmill running at ventilator threshold to exhaustion</td>
<td>↑ running time in ICE and CWI</td>
<td>↑ post-ex T&lt;sub&gt;re&lt;/sub&gt; (ICE &gt; CONT &gt; CWI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ running time between ICE and CWI</td>
<td>↓ T&lt;sub&gt;b&lt;/sub&gt; and T&lt;sub&gt;sk&lt;/sub&gt; in CWI</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ HR in CWI vs. ICE and CONT</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ RPE and thermal sensation in CWI and ICE</td>
</tr>
</tbody>
</table>

↑ = increased; ↓ = reduced; ↔ = no change; CONT = control; CWI = cold-water immersion; Glu = glucose; HCO<sub>3</sub> = bicarbonate; HR = heart rate; ICE = ice slurry; La⁻ = lactate; pH = potential hydrogen; RPE = reported perceived exertion; T<sub>b</sub> = body temperature; T<sub>c</sub> = core temperature; T<sub>re</sub> = rectal temperature; T<sub>sk</sub> = skin temperature; VO<sub>2</sub> = oxygen consumption
2.5.2 Pre-Cooling for Intermittent-Sprint Exercise Performance in the Heat

Pre-cooling literature has been traditionally dominated by the demonstrated benefits for endurance performance, particularly cycling, in hot conditions (Wegmann et al., 2012). Contrarily, however, where pre-cooling has been conducted before intermittent-sprint activity (Table 2.5.2), limited (Drust et al., 2000; Cheung & Robinson, 2004) to moderate gains in performance have been reported (Castle et al., 2006; Duffield & Marino, 2007). Drust and colleagues (2000) proposed that pre-cooling may be particularly pertinent for team-sports given the higher thermal strain accrued via intermittent as opposed to continuous exercise modalities (Ekblom et al., 1971). While the findings of these authors did not support this premise, it is noteworthy that improvements in intermittent-sprint performance have only been reported in studies conducted in warm-to-hot conditions (>30°C) (Wegmann et al., 2012). Perhaps unsurprisingly then, pre-cooling might be of greatest benefit to team-sport athletes where environmental heat stress exacerbates elevated metabolic heat gain; further, maximising pre-cooling stimulus, and thus physiological perturbations, may be required to evoke noticeable changes in performance (Duffield & Marino, 2007).

As evidence of this, Drust and colleagues (2000) utilised a 60 min cold shower to examine the effects of pre-cooling on soccer-specific intermittent exercise on a non-motorised treadmill. Having lowered T_r by ~0.6°C before commencing the 90 min protocol, no changes were incurred in heart rate, metabolic responses or perceived exertion. Most pertinent, a sustained reduction in thermal strain for the entirety of the exercise protocol showed no effect on total distance covered in normal (20.5°C; 9.5 ± 0.4 km), pre-cooled (20.5°C; 9.4 ± 0.6 km) and warm conditions (26°C; 9.3 ± 0.5 km). Likewise, Cheung and Robinson (2004) reported upper-body pre-cooling to provide no benefit to intermittent-sprint power output (pre-
cooling: 909 \pm 161 \text{ vs. control: } 921 \pm 163 \text{ W}) in thermo-neutral conditions (22°C), irrespective of lowered body temperatures. Even where environmental heat stress is increased (30°C), Duffield et al. (2003) showed brief ice-vest application (5 min pre- and 10 min mid-exercise) as ineffective in altering thermoregulatory responses to an 80 min intermittent-sprint cycling protocol. Collectively then, these studies could be interpreted to highlight the marked manipulation of thermal strain required (high passive/exertional heat gain and/or precooling heat loss) for any potential benefits to be incurred during team-sport like exercise (Skein et al., 2012).

Castle and colleagues (2006) were the first to report a benefit of pre-cooling on prolonged intermittent-sprint exercise in the heat (34°C), highlighting ice-pack application to the thighs to improve peak power output by \~4\%. Importantly, these data show the dose-specific effects of pre-cooling, as reductions in thermal load achieved were dependent on the intervention administered [water immersion (18°C) > ice packs (-16°C) > ice vest (11°C) > control (no cooling)]. All pre-cooling techniques reduced $T_{re}$ from rest during the 20 min intervention and warm-up period, though the rate of heat strain increase was higher in the control trial than experienced in water immersion and ice pack conditions ($P < 0.001$). That said, only ice-pack pre-cooling demonstrated main effects for increased work and power output compared to control ($P < 0.05$). Although the direct application and cooling of muscle tissue is seemingly counter-intuitive for high-intensity performance (Crowley et al., 1991; Sleivert et al., 2001), lowered $T_{mu}$ in the ice-pack trial dissipated within 16 min of exercise commencement, and was inversely correlated with peak power output ($r = -0.65; P < 0.01$) and work completed ($r = -0.70; P < 0.01$). Hence, given the comparable changes between conditions in $VO_2$, La$^-$ and perceived exertion, the authors concluded that the ice packs evoked the most favourable reduction in heat strain, reflecting changes to both $T_{re}$ and $T_{mu}$. 
Further, they speculated that the ensuing maintenance in power output may owe to optimal sensory feedback and improved motor unit recruitment (Castle et al., 2006).

A clear limitation of all of these studies, however, is the fixed-intensity exercise completed between maximal efforts that restrict the engagement of pacing strategies and fails to replicate the self-paced nature of team-sport activity (Duffield, 2008). Duffield and Marino (2007) report improved sub-maximal work rates following pre-cooling in an ice-bath (15 min, 11°C), regardless of any noticeable change in repeated sprint ability across an 80 min intermittent-sprint protocol in 32°C heat. Similarly, Skein et al. (2012) demonstrate whole-body cold-water immersion (10°C) before self-paced intermittent-sprint exercise (31°C) to maintain total distance covered during the final 10 min of a 50 min trial compared with passive heating (38°C) and thermo-neutral control interventions (19°C). This occurrence is also seemingly transferable to a training environment, as Duffield and co-authors (2009d) highlight lacrosse players to improve training distances covered after mixed-method pre-cooling, mainly owing to greater work completed at intensities of 7 – 14 km·h⁻¹ (3.35 ± 0.02 vs. 3.11 ± 0.13 km; P= 0.05). Underlying these divergent responses, it is proposed that the pre-cooling may protect against declines in neuromuscular function as evidenced by a greater maintenance of voluntary force and activation (Skein et al., 2012). Thus, increasing heat storage capacity via pre-cooling may alter feed-forward controls similar to those seen in endurance exercise (Kay et al., 2001) to sustain motor unit recruitment and so a higher pacing strategy during self-paced intermittent-sprint performance in the heat. Despite the potential effectiveness of pre-cooling for intermittent-sprint exercise, it remains relatively untested, particularly in team sports like cricket where physical demands and environmental conditions seem conducive to performance improvements generated with pre-cooling.
Table 2.5.2: Summary of studies examining the effects of pre-cooling on intermittent-sprint exercise performance.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Temperature</th>
<th>Cooling Intervention</th>
<th>Exercise Protocol</th>
<th>Performance Effects</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castle et al. (2006)</td>
<td>12</td>
<td>34°C</td>
<td>20 min of No cooling (CONT); Ice-vest (Vest); CWI; ice packs on upper legs (Packs)</td>
<td>40 min ISE including repeated bouts of 10s passive rest, 5s sprint, 105s active recovery</td>
<td>↓ PPO during CONT ↑ PPO during Packs (4%)</td>
<td>↓ rate of heat strain for CWI and Packs ↓ Tc, Tmm, and Tsk for CWI and Packs ↓ Thermal Strain and PSI following cooling</td>
</tr>
<tr>
<td>Cheung &amp; Robinson (2004)</td>
<td>10</td>
<td>22°C</td>
<td>Hooded ice-vest circulating 5°C water until Tc ↓ 0.5°C or garment was applied for 75 min</td>
<td>30 min continuous cycling at 50% VOpeak separated by repeated 10 s maximal sprints completed every 5 min</td>
<td>↔ mean and PPO</td>
<td>↓ Tb, Tsk, HR, thermal sensation ↔ VO2, La-, RPE</td>
</tr>
<tr>
<td>Clarke et al. (2010)</td>
<td>12</td>
<td>30.5°C</td>
<td>Pre-cool + CHO during ex (CHOc); pre-cool + PLA during ex (PLAc); no cooling + CHO (CHO); no cooling + PLA (PLA)</td>
<td>90 min soccer-specific intermittent-sprint exercise</td>
<td>↑ self-paced ex during CHOc compared to CHO and PLAc</td>
<td>↓ Tc, Tmm, and thermal sensation after cooling</td>
</tr>
<tr>
<td>Drust et al. (2000)</td>
<td>6</td>
<td>Hot (26°C) vs Neutral (20°C)</td>
<td>60 min of no cooling (CONT); cold shower (26°C)</td>
<td>90 min soccer-specific ISE protocol on a non-motorised treadmill</td>
<td>Sprint performance was not reported</td>
<td>↔VO2, HR, Vl, RPE, plasma La-, Glu, FFA</td>
</tr>
<tr>
<td>Duffield et al. (2003)</td>
<td>7</td>
<td>32°C</td>
<td>5 min of no-cooling (CONT); Ice-Vest (Vest) before and during recovery</td>
<td>80 min intermittent sprint cycling</td>
<td>↔ work done or PO during sprint performance</td>
<td>↑ chest Tsk, thermal discomfort, thirst ↔ HR, La-, Tc, Tsk, RPE, SwR, ratings of fatigue</td>
</tr>
</tbody>
</table>
Table 2.5.2: Summary of studies examining the effects of pre-cooling on intermittent-sprint exercise performance continued.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Temperature</th>
<th>Cooling Intervention</th>
<th>Exercise Protocol</th>
<th>Performance Effects</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duffield &amp; Marino (2007)</td>
<td>9</td>
<td>32°C</td>
<td>15 min of no cooling (CONT); Ice-bath (CWI) plus vest during WU and HT; Ice-vest (Vest)</td>
<td>60 min ISE including 15 m sprint every min and free-paced, sub-max efforts (hard run, jog, walk)</td>
<td>↔ sprint times and %decline</td>
<td>↑ T&lt;sub&gt;c&lt;/sub&gt;, T&lt;sub&gt;sk&lt;/sub&gt;, HR, SwR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ self-paced distance in CONT</td>
<td>↑ Thermal Comfort</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ distance covered during hard run efforts</td>
<td>↔ La&lt;sub&gt;i&lt;/sub&gt;, pH, K&lt;sup&gt;+&lt;/sup&gt; or Na&lt;sup&gt;+&lt;/sup&gt;</td>
</tr>
<tr>
<td>Duffield et al. (2009)</td>
<td>7</td>
<td>32°C</td>
<td>20 min mixed-method (vest, towels, packs)</td>
<td></td>
<td>↑ self-paced distance</td>
<td>↓ HR; ↔ RPE, TSS, IL-6, IGF-1 and IGF-BP3</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ peak speed and very-high-intensity efforts</td>
<td></td>
</tr>
<tr>
<td>Marsh &amp; Sleivert (1999)</td>
<td>13</td>
<td>29°C</td>
<td>30 min cold-water immersion (↓ T&lt;sub&gt;re&lt;/sub&gt; by 0.3°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skein et al. (2012)</td>
<td>10</td>
<td>31°C</td>
<td>15 min CWI (10°C); PH (38°C); CONT (19°C)</td>
<td>50 min ISE including 15 m sprint every min and free-paced, sub-max efforts (hard run, jog, walk)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleivert et al. (2001)</td>
<td>9</td>
<td>33°C</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

↑ = increased; ↓ = reduced; ↔ = no change; CONT = Control; CWI = cold water immersion; HR= heart rate; HT = half-time; IGF-1 = insulin-like growth factor 1; IGF-BP3 = insulin-like growth factor-binding protein 3; IL-6 = interlukin-6; ISE = Intermittent-Sprint Exercise; K<sup>+</sup> = potassium; La<sub>i</sub> = lactate; Na<sup>+</sup> = sodium; Packs = Ice-Packs; PH = passive pre-heating; PPO = Peak Power Output; PSI = Physiological Strain Index; SwR = sweat rate; T<sub>c</sub> = core temperature; T<sub>mu</sub> = muscle temperature; T<sub>re</sub> = rectal temperature; T<sub>sk</sub> = skin temperature; V<sub>E</sub> = minute ventilation; Vest = Ice-Vest; O<sub>2</sub> = oxygen consumption; VO<sub>2max</sub> = maximal aerobic capacity; WB = whole body; WU = warm-up.
2.5.3 Pre-Cooling for Skill Performance in the Heat

To date, few studies have examined the effects of pre-cooling in sports specific, field-based environments (Drust et al., 2000; Hornery et al., 2007a; Duffield et al., 2009; Duffield et al., 2011). Although the benefits to self-paced intermittent-sprint exercise is becoming clearer (Duffield & Marino, 2007; Skein et al., 2012), little attention has been directed towards the influence of pre-cooling on technical, skill-based components of sports performance. Hornery and colleagues (2007a) utilised a portable plunge pool (24°C) to cool tennis players for 30 min before simulated tennis match play, further administering a hooded cooling jacket to be worn during breaks in play. Pre-cooling initially increased $T_c$ (37.1 ± 0.2 vs. 36.9 ± 0.3°C) and reduced thermal sensation (2.3 ± 0.6 vs. 4.0 ± 0.1 AU) compared to the control condition ($P < 0.05$). However, there was no marked effect on physiological (HR, $T_c$, and sweat loss) or biochemical responses (La, Glu, CK, and prolactin) during match play. Most pertinent, however, the authors highlighted a non-significant trend for a lower ground stroke velocity after pre-cooling (117 ± 7 vs. 120 ± 8 km h$^{-1}$; $P= 0.26$; $d= 0.38$). Thus, they concluded that despite improved thermoregulatory control pre-match, seemingly little benefit is achieved by pre-cooling for tennis match-play. Given the mild environment conditions (21°C) and low heat strain ($T_c$ 37.6 ± 0.5°C), well below that previously reported as detrimental to physical and cognitive requirements of tennis (Bergeron et al., 2007; Hornery et al., 2007b), these findings are unsurprising. Nevertheless, the dearth of literature relating to the effects of pre-cooling on technical team sport performance requires attention and the exercise- and environment-induced heat stress commonly experienced by medium-fast bowlers offers an ideal model for study.
2.5.4 Mechanisms Related to Performance Improvements via Pre-Cooling

2.5.4.1 Physiological Mechanisms

Despite increasing support for the use of pre-cooling techniques before exercise in the heat, causal factors for the observed improvements in performance noted after pre-cooling remain speculative (Duffield, 2008; Wegmman et al., 2012). The most obvious associations relate to the magnitude of thermal change, whereby greater heat storage capacity can accommodate higher rates of metabolic heat gain, thus extending the maintenance of high-intensity exercise prior to the attainment of a critical limiting temperature (Marino, 2002). Indeed, the dose-specific response to pre-cooling has been reflected in the larger cooling stimuli leading to greater performance benefits during exercise in the heat (Duffield & Marino, 2007; Quod et al., 2008; Ross et al., 2011). Bogerd and others (2010) highlight the dose-specific responses in heat storage capacity with lower pre-cooling temperatures (control: 7.7 ± 5.7 vs. mild (evaporative cooling): 21.2 ± 5.1 vs. strong (ice-vest): 39.5 ± 8.4 Wm$^{-2}$) reflected in improvements in cycling time to exhaustion in warm conditions (29°C). While this dose-response assumption is well supported (Lee & Haymes, 1995; Booth et al., 1997; Kay et al., 1999), the potentially adverse effects of a larger external pre-cooling dose in reducing $T_{\text{max}}$ (Sleivert et al., 2001), irrespective of the strategy applied (Castle et al., 2006), questions how this may be ideally accomplished (Siegel et al., 2012). Moreover, considering recent evidence against a critically limiting temperature (Ely et al., 2009), it might be argued that heat storage is not a mechanism per se, rather, it precedes a cascade of cardiovascular, metabolic and neural events that maintain exercise performance in the heat.

Pre-cooling has been well documented to blunt the rise of $T_c$ associated with exercise- and environment-induced heat stress, protecting centralised blood volume as the need for heat
losses at the periphery are reduced (Marino, 2002). Together with sustained conductive and convective thermal controls, lowered sweat rates for evaporative heat loss preserves blood volume, thereby increasing both venous pressure and return (Casa, 1999). This reduction in cardiovascular strain is reflected in the lower heart rates reported after pre-cooling during steady-state exercise (Schmidt & Brück, 1981; Hessemer et al., 1984; Lee & Haymes, 1995). Likewise, Duffield et al. (2010) show similar heart rates during self-paced exercise, despite performing at a higher power output in pre-cooling trials. Schmidt and Brück (1981) hypothesised that the improved cardiovascular control achieved with pre-cooling may slow arteriovenous anastomoses opening to allow higher oxygen uptake. However, this explanation as a mechanism of performance improvement fails to account for the mismatch in reductions in heart rate having dissipated within ~15 min of self-paced exercise commencement (Marino, 2002), well prior to ergogenic benefits being observed (Duffield et al., 2010). Accordingly, although lower body temperatures may ease initial cardiovascular strain, it remains difficult to reason how this by-product of pre-cooling might improve performance; particularly where lesser heart rates observed in constant-intensity exercise models are indiscernible during self-paced activities as athletes complete at a similar cardiovascular strain (Marino et al., 2000; Duffield et al., 2010).

Alternatively, reductions in $T_{sk}$, independent of changes to $T_{c}$, may also be associated with the regulation of self-paced exercise intensity. Kay and colleagues (1999) indicate that pre-cooling of the skin alone is effective in reducing thermal strain and increasing self-paced cycling performance in environmental temperatures of 31°C. More specifically, lowering $T_{sk}$ by ~5 – 6°C via whole-body water immersion (26°C) still increased heat storage and lowered sweat rates, though most importantly appears to increase pacing strategies irrespective of commencing $T_{re}$ (Kay et al., 1999). Further, Schlader et al. (2011), demonstrate a lowered
commencing $T_{sk}$ (29.4 ± 0.9 vs. 35.2 ± 0.6°C) to be associated with a higher self-selected power output maintained for the first three quarters of a 60 min time trial. Collectively, these findings point to $T_{sk}$ providing important signalling input to the regulation of exercise performance (Schlader et al., 2010; Jay, 2009). It could be argued that the higher initial power outputs and lower thermal perception reported by Schlader and colleagues (2011) might support an integrative physiological and perceptual model of anticipatory regulation in exercise performance (Tucker, 2009; Noakes, 2012a). Regardless, blunted body temperature responses ($T_c$ and/or $T_{sk}$) to exercise in the heat seemingly attenuate the development of fatigue, thus maximising the period of optimal self-selected exercise intensity before any thermally-induced override to sustain thermal control (Marino, 2002).

2.5.4.2 Neuromuscular Mechanisms

The ‘critical limiting temperature’ has traditionally been proposed to impair voluntary exercise capacity as evidenced by exercise cessation with the attainment of a particular $T_c$ (~40°C) (Nielsen et al., 1993; González-Alonso et al., 1999). However, given the problematic associations between exercise intensity and isolated markers of cardiovascular, thermoregulatory and metabolic load (Marino, 2004), the integrated effects of pre-cooling on CNS motor output during exercise in the heat offers an alternate interpretation (Marino, 2002). High endogenous thermal loads reduce force production, as CNS drive to the muscle is reportedly inhibited by elevated temperatures (Nybo, 2012), energy turnover (Nybo et al., 2003), oxygenation and blood flow to the brain (Nybo & Rasmussen, 2007). Accordingly, these unfavourable cerebral perturbations are likely to reduce muscle recruitment patterns, potentially explaining diminished exercise capacity in the heat (Tucker et al., 2004). Evidently, Skein and others (2012) highlight a greater maintenance of voluntary force and
activation after pre-cooling to protect optimal pacing strategies during self-paced intermittent-sprint performance under heat stress (31°C). This notion of improved central drive after pre-cooling has been shown with the reduction of voluntary drive during maximal isometric contractions when in a hyperthermic state (Nybo & Nielsen 2001a; Saboisky et al. 2003), but returns to baseline values once cooling is applied and $T_c$ is reduced (Morrison et al. 2004; Thomas et al. 2006). As such, it is possible that thermal advantages achieved by pre-cooling may safeguard neuromuscular pathways, protecting exercise performance in the heat and potentially explain the maintenance of higher exercise intensities (Kay et al., 1999; Duffield et al., 2010). Even so, current evidence supporting this hypothesis is lacking (Skein et al., 2012) and understanding of the interplay between central and peripheral mediators (heat strain and previous contractile activity) remains to be fully elucidated (Périard et al., 2011a).

### 2.5.4.3 Perceptual Mechanisms

The perception of effort during exercise represents a subjective manifest of integrative signalling to alter exercise intensities, likely originating from both central and peripheral origins (Borg, 1982; Smirmaul, 2012). Tucker and colleagues (2006) previously proposed that afferent signalling of cutaneous thermoreceptors subconsciously down-regulate exercise intensity to maintain thermal homeostasis in relation to the RPE response. Elevated thermal loads are known to increase RPE at a given exercise intensity (Maw et al., 1993; Galloway & Maughan, 1997), with $T_{sk}$ in particular contributing to higher sensations of thermal discomfort (Schlader et al., 2011). Notably, however, RPE responses appear to be preserved during self-paced exercise, regardless of attempted disruption to homeostasis (Tucker, 2009; Schlader et al., 2010). Demonstrated reductions in RPE and/or thermal sensation during
exercise in the heat after pre-cooling are commonly reported (Arngrímsson et al., 2004; Castle et al., 2006; Skein et al., 2012), though not always uniformly throughout the literature (Drust et al., 2000; Duffield et al., 2009d; Ross et al., 2011). Still, despite these discrepancies, it could be postulated that the reductions in exercise intensity apparent without pre-cooling may occur to protect the RPE response in hot conditions (Schlader et al. 2010). Of course the alternate argument, as offered by Marcora (2007), is that these altered pacing strategies owe to the conscious awareness of thermal state. Irrespective as to whether these changes in RPE and thermal sensation are conscious or otherwise, Barwood et al. (2011) recently highlighted the inherent need for a thermoregulatory change, as improved perceptual strain using menthol spray failed to alter 40 km time trial performance in 32°C heat. Accordingly, where pre-cooling is administered before exercise in the heat, blunted increases in body temperature and perceptual strain may assist in maintaining self-selected pacing strategies (St Clair Gibson et al., 2006). Furthermore, from a cricket perspective the contributions of perceptual elements for performance improvement should not be overlooked, particularly where the lesser RPE experienced after pre-cooling may attenuate fluctuations in subjective external inputs (i.e. crowd support and scoreboard pressure) (Noakes, 1992; St Clair Gibson et al., 2006).
2.6 Post-Exercise Cooling for Recovery of Performance in the Heat

The combination of high ambient temperatures and increasing metabolic heat loads accompanying exercise exacerbates physiological strain and reduces performance in ensuing bouts (Maughan & Shirreffs, 2004; Duffield, 2008). Indeed, a 60 min passive recovery in 33°C heat following 30 min of intermittent-sprint cycling slows neuromuscular thermoregulatory, cardiovascular and perceptual recovery compared to thermo-neutral temperatures (22°C) (Duffield et al., 2009c). Accordingly, for cricketers, where same- and/or next-day performance is required, post-exercise cooling may rapidly ease thermal strain and so increase rates of recovery (Vaile et al., 2008a; Barwood et al., 2009; Peiffer et al., 2010). Cold-water immersion is a popular athletic aid and is speculated to improve recovery by altering blood flow and reducing T_{mu} to minimise inflammatory events and muscle soreness (Wilcock et al., 2006; Leeder et al., 2012). Nevertheless, increasing discrepancies in the laboratory-interventions examined (i.e. cold-water immersion) and the practical demands of field-based use (i.e. low cost, high portability and brief time constraints) has recently presented challenges for cold therapies following exercise (Barwood et al., 2009). Current understanding of alternate cooling techniques in comparison with cold-water immersion is limited (DeMartini et al., 2011), though may be integral to further elucidate the mechanisms of post-exercise cooling and best cater for the sport-specific requirements in the field.
2.6.1 Post-Exercise Cooling for Recovery of Self-Paced Exercise Performance in the Heat

The regulation of self-selected exercise intensity is purported to preserve physiological homeostasis so as to avoid catastrophic failure (Noakes, 2012a). In the heat, high thermal strain down-regulates acute pacing strategies (Marino, 2004; Tucker et al., 2004), while integrated feed-forward/feedback signalling of exercise duration and environmental temperature might also suppress work rate in repeated bouts where unfavourable heat strain has not been alleviated (Tucker et al., 2009). While this occurrence is detrimental to self-paced exercise, thermal inhibition of physical recovery may be particularly pertinent to team sports where match strategy and activity patterns are also adjusted in response to opposition demands. Halson et al. (2008) reported a three minute cold-water immersion (3 x 60 s repetitions) to hasten heart rate recovery (CWI Δ116 ± 9 vs. CONT Δ106 ± 4 bpm; P= 0.02) and reduce T_{re} (CWI Δ1.99 ± 0.50 vs. CONT Δ1.49 ± 0.50°C; P= 0.01) during a 40 min period following a cycling time trial in 34°C heat. Correspondingly, Barwood and others (2009) report larger reductions in thermal load (physiological and perceptual) using practical cooling methods (phase change garment > whole body fanning > hand immersion > liquid cooled garment > air cooled garment > control) to similarly maintain self-paced running distances achieved before the attainment of given internal temperature. It is pertinent, however, that despite a lowered T_{re}/T_{sk} and a self-paced exercise task, Barwood and others (2009) reported no change in running speed during the repeated effort, raising questions as to how and or why pacing may be affected by post-exercise cooling.

Although not disclosed in-text, the findings of Barwood et al. (2009) would be fundamentally limited if the participants were consciously aware of impending task termination (T_{re}
38.5°C) in an open-ended exercise task. Nevertheless, reduced heat strain achieved using post-exercise cooling has also been highlighted to permit higher self-selected exercise intensities during ensuing performance-based trials (Yeargin et al., 2006; Vaile et al., 2008a; Peiffer et al., 2010a). Yeargin and co-authors (2006) show a 12 min cold-water immersion (14°C) to lower elevated post-exercise T\textsubscript{re} following a 90 min trail run by ~2.1°C and improve 2 mile race time by 6% compared to control. Further, Peiffer and colleagues (2010a) associated a 0.5°C reduction in T\textsubscript{re} achieved with a 5 min cold-water immersion (14°C) to maintain a higher mean power output (327.9 ± 55.7 vs. 288.0 ± 58.8 W) and improve cycling performance in a subsequent 4 km time trial. Moreover, as VO\textsubscript{2} and cycling economy were unaffected by post-exercise cooling, the authors pointed to the decreased T\textsubscript{re} to explain the corresponding reduction in RPE throughout a fixed-intensity component of the protocol (Peiffer et al., 2010a). Nevertheless, even as the collective findings point to the importance of endogenous heat losses, some caution must be advised as these absolute changes in mean body temperature may not necessarily reflect an improved performance in hot conditions (Yeargin et al., 2006; Vaile et al., 2008a).

While supporting evidence for the use of post-exercise cooling between repeated bouts in the heat is growing (Table 2.6.1), focus on same-day performances have taken precedence over the effects on exercise performance across consecutive days. Vaile and others (2011) reported post-exercise cold-water immersion to maintain repeated cycling time trial performance, alleviating declines in self-selected power output otherwise observed with an active recovery within an hour of exercise completion (Vaile et al., 2008a). These findings are not dissimilar to those of Rowsell and colleagues (2011) who demonstrate cold-water immersion to protect against declines in total running distances across four days of soccer tournament match-play. However, a time-course difference in recovery responses after cold therapy raises the
possibility of divergent mechanisms being engaged to achieve a similar outcome. The neuromuscular responses reported by Pointon et al. (2012) after self-paced intermittent-sprint exercise under heat stress could indicate cold therapies to manipulate CNS drive as well as potential dysfunction at the cellular level. Still, how this might influence muscle recruitment patterns and so self-selected work rates on consecutive days in hot conditions remains to be identified.

The mediation of potentially divergent fatiguing agents might assist to explain these inconsistencies relating to transient and cumulative declines in neuromuscular performance following self-paced exercise in the heat (Peiffer et al., 2009a; Pointon et al., 2012). One rationale for post-exercise cooling is to alleviate the deleterious effects of high $T_c$ on CNS drive (Duffield, 2008), hastening the return of acute neuromuscular function as demonstrated through higher voluntary force and activation post-recovery (Pointon et al., 2012). However, external cooling techniques, like cold-water immersion, may adversely decrease $T_{mu}$ in relation to the intervention duration used (Peiffer et al., 2009b). Further, related reductions in femoral vein diameter (9%) after a 20 min cold-water immersion (14°C) have been associated with a 13% lessening in isometric quadriceps force (Peiffer et al., 2009a). Nevertheless, detrimental effects of cold-water immersion in reducing MVC force at 24 h, as per Pointon et al. (2012), is perplexing when considering the traditional hypothesis pertaining to lowered temperature and blood flow in easing muscle damage (Eston & Peters, 1999; Bailey et al., 2007). While these neuromuscular assessments offer insight into isolated muscle function, it is unfortunate that additional consideration for prolonged self-paced exercise in the heat has not been examined.
Table 2.6.1 Summary of studies examining the effects of post-exercise cooling on recovery after self-paced exercise in the heat.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Temperature</th>
<th>Cooling Intervention</th>
<th>Exercise Protocol</th>
<th>Performance Effects</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barwood et al. (2009)</td>
<td>9</td>
<td>31°C</td>
<td>Hand immersion (17°C); WBF (3.5-3.80 m s(^{-1})); ACG (1801 min(^{-1})); LCG (-500mL saline, ≤12.3°C); PCG (heat extraction = 211.7 kJ kg(^{-1})); CONT</td>
<td>Maximal self-paced treadmill running ceased once T(_{re})= 38.5°C</td>
<td>↑ self-paced running distance covered after HI and WBF than CONT LCG and ACG</td>
<td>Maximal self-paced treadmill running ceased once T(_{re})= 38.5°C</td>
</tr>
<tr>
<td>Buchheit et al. (2009)</td>
<td>10</td>
<td>35°C</td>
<td>5 min, CWI (14°C)</td>
<td>2 x supramaximal cycling bouts separated by 20 min</td>
<td>↔ cycling performance</td>
<td>↔ T(_{re}), HR recovery</td>
</tr>
<tr>
<td>Clements et al. (2002)</td>
<td>17</td>
<td>27°C</td>
<td>12 min, CWI (14°C); IWI (5°C); MT (no water, 29°C)</td>
<td>19 km hilly trail run</td>
<td>NA</td>
<td>↔ cooling rate in CWI and IWI</td>
</tr>
<tr>
<td>Halson et al. (2008)</td>
<td>11</td>
<td>34°C</td>
<td>3x60 s CWI (11.5°C); CONT (passive recovery, 24°C)</td>
<td>40 min cycling time trial</td>
<td>NA</td>
<td>↓ cooling rate in CWI and IWI 8-12 min vs. MT</td>
</tr>
<tr>
<td>Peiffer et al. (2009a)</td>
<td>10</td>
<td>32°C</td>
<td>20 min, CWI (14°C)</td>
<td>90 min CP (216 ± 12 W) cycling followed by a 16.1 km time trial</td>
<td>↓ post-ex voluntary and superimposed MVC torque</td>
<td>↓ HR, T(<em>{re}), T(</em>{sk}) 9%</td>
</tr>
<tr>
<td>Peiffer et al. (2009b)</td>
<td>12</td>
<td>40°C</td>
<td>5, 10, 20 min CWI (14°C)</td>
<td>Cycling time to exhaustion at ventilatory threshold</td>
<td>↔ Isometric and isokinetic torque</td>
<td>↓ T(_{re}) vs. CONT 10 and 20 min &lt; 5 min &lt; CONT</td>
</tr>
<tr>
<td>Peiffer et al. (2010a)</td>
<td>10</td>
<td>35°C</td>
<td>5 min, CWI (14°C)</td>
<td>Repeated 25 min CP (254±22 W) cycling followed by a 4km time trial</td>
<td>↑ cadence CP2 ↓ time trial completion time ↓ time trial mean power output</td>
<td>↓ T(_{re}) CP2 and TT2 ↔ VO(_2) and exercise economy ↓ CP2 RPE</td>
</tr>
</tbody>
</table>
Table 2.6.1 Summary of studies examining the effects of post-exercise cooling on recovery after self-paced exercise in the heat continued.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Temperature</th>
<th>Cooling Intervention</th>
<th>Exercise Protocol</th>
<th>Performance Effects</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peiffer et al. (2010b)</td>
<td>10</td>
<td>35°C</td>
<td>5 min, CWI (14°C)</td>
<td>Repeated 1 km cycling time trial</td>
<td>↔ maximal isokinetic concentric torque</td>
<td>↔ T&lt;sub&gt;re&lt;/sub&gt;</td>
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<tr>
<td></td>
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<td></td>
<td>2x30 min self-paced intermittent-sprint exercise</td>
<td>↑ MVC and VA post-intervention</td>
<td>↓ T&lt;sub&gt;mu&lt;/sub&gt; after 2&lt;sup&gt;nd&lt;/sup&gt; time trial</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ MVC and VA 24h post-exercise</td>
<td>↓ T&lt;sub&gt;e&lt;/sub&gt;, HR and MS post-intervention</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↔ repeated sprint ability</td>
<td>↑ Voluntary EMG of the quadriceps post-intervention</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ Voluntary EMG of the quadriceps 24h post-exercise</td>
<td>↓ HCO&lt;sub&gt;3&lt;/sub&gt;</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ MVC post-intervention</td>
<td>↓ = reduced; ↔ = no change; ↑ = increased; ACG = air cooled garment; ACT = active recovery; AST = CK = creatine kinase; CP = constant pace; CRP = C-reactive protein; CWI = cold-water immersion; EMG = electromyography; ESQ = environmental symptoms questionnaire; HCO&lt;sub&gt;3&lt;/sub&gt; = bicarbonate; IGF-1 = insulin-like growth factor 1; IL-6 = interleukin-6; IWI = ice-water immersion; LCG = liquid cooled garment; MAP = mean arterial pressure; MT = mock treatment; MVC = maximal voluntary contraction; PCG = phase change garment; pH = ; PPO = peak power output; RPE = reported perceived exertion; T&lt;sub&gt;b&lt;/sub&gt; = body temperature; T&lt;sub&gt;es&lt;/sub&gt; = oesophageal temperature; T&lt;sub&gt;mu&lt;/sub&gt; = muscle temperature; T&lt;sub&gt;re&lt;/sub&gt; = rectal temperature; T&lt;sub&gt;sk&lt;/sub&gt; = skin temperature ; WBF = whole body fanning.</td>
</tr>
<tr>
<td>Pointon et al. (2012)</td>
<td>10</td>
<td>32°C</td>
<td>20 min, CWI (9°C)</td>
<td>Repeated 15 min CP (75% PPO) cycling followed by a 15 min time trial</td>
<td>↑ maintenance of total work vs. ACT</td>
<td>T&lt;sub&gt;b&lt;/sub&gt;, RPE, thermal sensation</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>All CWI recoveries ↑</td>
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<td></td>
<td>T&lt;sub&gt;es&lt;/sub&gt;, HR vs. ACT</td>
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<td></td>
<td>Intermittent CWI ↓ pre-E2</td>
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<tr>
<td>Vaile et al. (2008a)</td>
<td>10</td>
<td>34°C</td>
<td>15 min, intermittent CWI (1 min in and 2 min out, 10°C, 15°C, 20°C); continuous CWI (20°C); ACT (cycling, 40% VO&lt;sub&gt;2peak&lt;/sub&gt;)</td>
<td>Repeated 15 min CP (75% PPO) cycling followed by a 15 min time trial</td>
<td>↑ maintenance of total work vs. ACT</td>
<td></td>
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<td>All CWI recoveries ↑</td>
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<td>T&lt;sub&gt;es&lt;/sub&gt;, HR vs. ACT</td>
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<td></td>
<td>Intermittent CWI ↓ pre-E2</td>
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<td>↑ maintenance of cycling performance</td>
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<tr>
<td>Vaile et al. (2011)</td>
<td>10</td>
<td>33°C</td>
<td>15 min, CWI (15°C); ACT (cycling at 40% PPO)</td>
<td>2 x 35 min maximal cycling bouts</td>
<td>↑ maintenance of cycling performance</td>
<td>↓ T&lt;sub&gt;es&lt;/sub&gt;, HR, arm/leg blood flow</td>
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<td></td>
<td>↓ T&lt;sub&gt;es&lt;/sub&gt;, T&lt;sub&gt;b&lt;/sub&gt;, RPE, thermal sensation</td>
<td></td>
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<tr>
<td>Yeargin et al. (2006)</td>
<td>15</td>
<td>27°C</td>
<td>12 min; CWI (14°C), IWI (5°C); MT (no water, 29°C)</td>
<td>90 min trail run</td>
<td>↑ 2 mile race performance (6%) in CWI vs. MT</td>
<td>↓ HR, T&lt;sub&gt;re&lt;/sub&gt; in CWI and IWI</td>
</tr>
</tbody>
</table>

↑ = increased; ↓ = reduced; ↔ = no change; ACG = air cooled garment; ACT = active recovery; AST = CK = creatine kinase; CP = constant pace; CRP = C-reactive protein; CWI = cold-water immersion; EMG = electromyography; ESQ = environmental symptoms questionnaire; HCO<sub>3</sub> = bicarbonate; IGF-1 = insulin-like growth factor 1; IL-6 = interleukin-6; IWI = ice-water immersion; LCG = liquid cooled garment; MAP = mean arterial pressure; MT = mock treatment; MVC = maximal voluntary contraction; PCG = phase change garment; pH = ; PPO = peak power output; RPE = reported perceived exertion; T<sub>b</sub> = body temperature; T<sub>es</sub> = oesophageal temperature; T<sub>mu</sub> = muscle temperature; T<sub>re</sub> = rectal temperature; T<sub>sk</sub> = skin temperature ; WBF = whole body fanning.
2.6.2 Post-Exercise Cooling for Recovery of Intermittent-Sprint Exercise Performance in the Heat

Team sport athletes, including cricketers, are constantly challenged by limited recovery times between training or competition bouts; particularly when compromised post-session physiological states are likely to adversely impact on subsequent performance (Montgomery et al., 2008). While post-exercise cooling may hasten the return of neuromuscular function (Pointon et al., 2012), inconsistencies in translation of isolated joint force to whole-body functional performance are noteworthy (Table 2.6.2), perhaps attributable to the discrepancies in sports-specific demands and varied intervention protocols. Nevertheless, improved neuromuscular recovery (Bailey et al., 2007; Ascensão et al., 2011; Pournot et al., 2011) and maintained whole-body physical performance (Montgomery et al., 2008; Ingram et al., 2009; Rowsell et al., 2011) have been repeatedly demonstrated following cold-water immersion recoveries. It is surprising, however, that given the detrimental effects of high thermal strain on recovery of voluntary and evoked force (Duffield et al., 2009c), limited data have been reported on intermittent-sprint exercise in the heat (Pointon et al., 2012). Thus, despite commentaries on the thermally challenging environments often encountered at major sporting events (Olympic Games, Football World Cup, and Cricket World Cup) (Bergeron et al., 2012), attempted use of post-exercise cooling to protect ensuing performance in the heat (Wegmann et al., 2012) remains largely unexamined in a recovery context (Duffield, 2008).

Pointon and colleagues (2012) were the first to examine cold-water immersion recovery (9°C) after intermittent-sprint exercise in 32°C heat. Participants completed 2 x 30 min bouts of a self-paced intermittent-sprint protocol, involving a 15 m sprint every minute, separated by sub-maximal efforts at hard running, jogging and walking intensities. The authors report...
higher voluntary force and activation immediately following cold-water immersion, though this trend was reversed 24 h post-recovery (Pointon et al., 2012). Interestingly, cold-water immersion did not alter recovery of repeated sprint ability. These data highlight the differing responses of single joint, isometric contractions and dynamic whole-body exercise; but may also indicate the recovery effects of post-exercise cooling to be time dependent in hot conditions. While near immediate improvements in MVC force might be explained by a faster rate of $T_c$ reduction alleviating impaired CNS drive (Morrison et al., 2004; Thomas et al., 2006), lowered next-day neuromuscular function contrasts previous descriptions of maintained performance in thermo-neutral conditions (Bailey et al., 2007; Ingram et al., 2009; Pournot et al., 2011). It might be speculated that the cold-water immersion administered by Pointon et al. (2012) under heat stress was ineffective in lowering $T_{nu}$ and so in reduction of inflammatory events (Eston & Peters, 1999). Indeed, this could explain the lack of change in muscle damage markers as reported elsewhere (Bailey et al., 2007; Ingram et al., 2009), though given the tenuous link between biochemical perturbations and functional status, mechanistic causality is unclear (Baird et al., 2012).

Although cold-water immersion is accepted as the ‘gold standard’ of post-exercise cooling in the heat, concern over the logistical feasibility of this method has increased experimental focus on alternative techniques (Barwood et al., 2009; DeMartini et al., 2011). DeMartini and others (2011) compared the effects of nine post-exercise cooling techniques (cold-water immersion, shade, Port-a-Cool fan, Emergency Cold Containment System, Rehab Hood, Game Ready Active Cooling Vest, Nike ice-vest, ice buckets, and ice towels) after intermittent-sprint activity (small-sided games) in warm conditions (WBGT 27°C). After a 10 min post-exercise cooling period, thermal sensation was reduced in all trials where cooling was applied. However, declines in post-exercise $T_{re}$ (38.7°C) were only achieved using cold-
water immersion (-0.65°C), a whole-body cooling suit (-0.68°C) and ice-bucket cooling of the hands and feet (-0.74°C). These findings show dose-specific reductions in thermal strain, with most successful interventions listed above covering a larger surface area or providing a greater cooling stimulus than fanning, a cooling hood, iced towels and ice-vest methods, respectively (DeMartini et al., 2011). Similarly, reapplication of an ice-vest during the halftime interval of simulated soccer activities in hot conditions (31°C) augments pre-cooling effects, reducing final heat content by ~2.2 and 1.1 J g⁻¹ compared to no cooling and pre-cooling alone (Price et al., 2009). Nevertheless, as neither group of authors report any exercise performance results (Price et al., 2009; DeMartini et al., 2010), conclusions drawn from the acute thermoregulatory effects of post-exercise cooling makes inferences on the recovery of intermittent-sprint performance difficult.

Irrespective of ambient temperature, much of the basis for post-exercise cooling derives from sports medicine principles relating to improved recovery of soft-tissue injury (Leeder et al., 2012) and potential links between lowered muscle damage profiles and a faster functional recovery (Bailey et al., 2007; Ascensão et al., 2011). Eston and Peters (1999) reported no effect of cold-water immersion on the recovery of elbow flexor strength or muscle tenderness, despite a greater relaxed elbow angle and lower creatine kinase activity at 48 and 72 h. In contrast, Bailey et al. (2007) show greater maintenance of MVC force during the initial 48 h after intermittent shuttle-running; yet despite an attenuated myoglobin peak 1 h post-exercise, cold-water immersion demonstrated no effect on creatine kinase response. Of most relevance to intermittent-sprint performance, albeit in thermo-neutral conditions, Ascensão and colleagues (2011) investigated the effects of cold-water immersion on the recovery of physical performance and muscle damage following a one-off soccer match. Of note in this applied setting, the 10 min cold-water (10°C) recovery blunted biochemical
responses of damage and inflammation (creatine kinase, myoglobin, C-reactive protein) within 30 min, and particularly by 24 h post-exercise. Coupled with reduced muscular soreness, the maintenance of voluntary force reported by Ascensão et al. (2011) indicates a faster return of post-match neuromuscular function, possibly explaining sustained physical performances apparent when using post-exercise cooling in tournament scenarios (Montgomery et al., 2008; Rowsell et al., 2011).
Table 2.6.2: Summary of studies examining the effects of post-exercise cooling on recovery after intermittent-sprint exercise.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Exercise Protocol</th>
<th>Cooling Intervention</th>
<th>Performance Effects</th>
<th>Physiological Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascensão et al. (2011)</td>
<td>20</td>
<td>Friendly soccer match</td>
<td>10 min, CWI (10°C); TWI (35°C)</td>
<td>↑ MVC 24 post-exercise ↓ decline in SJ (24h) and CMJ (24h, 48h) ↔ sprint time</td>
<td>↓ CK (30min, 24h, 48h), Mb (30min), CRP (30min, 24h, 48h) ↓ DOMS of quadriceps and calf (24h) and hip adductors (30min) ↓ Mb 1h post-exercise ↔ HR, Tc, and CK ↓ MS 1, 24 and 48h post-exercise ↑ perceived coldness during recovery</td>
</tr>
<tr>
<td>Bailey et al. (2007)</td>
<td>20</td>
<td>90 min intermittent shuttle-run</td>
<td>CWI (10 min, 10°C); CONT</td>
<td>↑ MVC 24 and 48h post-exercise ↔ VJ and sprint times</td>
<td>NA</td>
</tr>
<tr>
<td>Banfi et al. (2007)</td>
<td>30</td>
<td>Rugby Union</td>
<td>ACT+CWI (10min cycling at 180 W + 10min CWI of legs); CWI+ACT (10min CWI of legs + 10min cycling at 180 W); PAS 10 min, CWI (14°C); shade; fanning; ECCS (7-16°C); cooling hood; GRV; NIV; ice buckets (14°C); ice towels; CONT</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>DeMartini et al. (2011)</td>
<td>16</td>
<td>Small-sided games</td>
<td>5 min CWI (10-12°C); CWT (7 x 60 s cycles alternating 10-12°C and 38-40°C); CONT</td>
<td>↔ phosphate decrement test and 300m test.</td>
<td>CWI, ECCS and ice buckets ↓ T&lt;sub&gt;e&lt;/sub&gt; and HR post-intervention All cooling ↓ thermal sensation, except shade ↔ thirst sensation CWI, fanning and ice towels ↓ Environmental Symptoms Questionnaire scores</td>
</tr>
<tr>
<td>Higgins et al. (2011)</td>
<td>26</td>
<td>Rugby Union training session</td>
<td>5 min CWI (10-12°C); CWT (7 x 60 s cycles alternating 10-12°C and 38-40°C); CONT</td>
<td>↔ phosphate decrement test and 300m test.</td>
<td>CWI ↓ MS CWT ↓ MS 24h post-exercise ↔ CK and CRP</td>
</tr>
<tr>
<td>Ingram et al. (2009)</td>
<td>11</td>
<td>80 min simulated team sports exercise and 20 m shuttle run test to exhaustion</td>
<td>CWI (6°C); CWT (7 x 60 s cycles alternating 10-12°C and 38-40°C); CONT</td>
<td>CWI ↓ decline in isometric leg extension and flexion strength 48h post-exercise 24 and 24h post-exercise CWI ↓ decline in 20 m sprint performance 48h post-exercise</td>
<td>↓ DOMS of quadriceps and calf (24h) and hip adductors (30min) ↓ Mb 1h post-exercise ↔ HR, Tc, and CK ↓ MS 1, 24 and 48h post-exercise ↑ perceived coldness during recovery</td>
</tr>
</tbody>
</table>
Table 2.6.2: Summary of studies examining the effects of post-exercise cooling on recovery after intermittent-sprint exercise continued.

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Exercise Protocol</th>
<th>Cooling Intervention</th>
<th>Performance Effects</th>
<th>Physiological Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>King &amp; Duffield (2009)</td>
<td>10</td>
<td>Simulated Netball</td>
<td>CWI (9°C); CWT (5 cycles alternating 10°C (60 s) and 39°C (120 s)); ACT (40% v-VO₂max); CONT</td>
<td>↔ VJ, 10m sprint, 20m sprint, total-circuit time</td>
<td>CWI ↓ Tₖ</td>
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<td>CWI and CWT ↓ decline in 5x20m spell and VJ 24 h post-exercise</td>
<td>CWT ↓ [La⁻] vs. ACT</td>
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<td></td>
<td>ACT ↑ HR and ↓ pH post-intervention</td>
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<td></td>
<td></td>
<td></td>
<td>CWI and CWT ↓ MS post-intervention</td>
</tr>
<tr>
<td>Kinugasa &amp; Kilding (2009)</td>
<td>28</td>
<td>90 min junior soccer match</td>
<td>CWI+ACT (3 cycles, 1min CWI (12°C) and 2min cycling (60-80rpm, 90-110W); CWT (3 cycles, 1min CWI (12°C) and 2min hot shower (38°C); PASS (7min static stretching, 2min sustained leg raises)</td>
<td>↔ VJ 24 h post-match</td>
<td>CWI+ACT ↑ perceived recovery and ↓ thermal sensation post-intervention</td>
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<td></td>
<td></td>
<td>CWI+ACT ↓ feelings of leg heaviness after recovery and 24 h post-match</td>
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<td></td>
<td>CWT ↓ feelings of leg heaviness after recovery</td>
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<tr>
<td>Pournot et al. (2011)</td>
<td>41</td>
<td>2 x 10 min periods of CMJ and rowing</td>
<td>15 min, CWI (10°C); TWI (36°C); CWT (10 x 90 s cycles alternating 10 and 42°C); CONT</td>
<td>CWI maintained MVC and CMJ 1h and 24h post-exercise</td>
<td>CWI ↓ leucocytes 1h and CK 24 h post-exercise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rotations</td>
<td></td>
<td>CWT maintained MVC and CMJ 24h post-exercise</td>
<td>CWT ↑ LDH 1h post-exercise</td>
</tr>
<tr>
<td>Montgomery et al. (2008)</td>
<td>29</td>
<td>3-day basketball tournament</td>
<td>CWI (5 min, 11°C); CHO+STR (7.7g kg⁻¹ day⁻¹); CG (18 mmHg, ~18 h)</td>
<td>CWI maintained 20m speed, line-drill performance and flexibility</td>
<td>CWI and CG ↓ MS and general fatigue</td>
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<td>CWI ↓ thigh girth</td>
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<td>↓ MS and general fatigue on day 4</td>
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<td></td>
<td>↔ CK, MB, FABP LHD, IL-1b, IL-6 and IL-10.</td>
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<tr>
<td>Rowsell et al. (2009)</td>
<td>20</td>
<td>4-day junior soccer tournament</td>
<td>5 x 1 min, CWI (10°C); TWI (34°C)</td>
<td>↔ RSA and CMJ</td>
<td>↓ MS and general fatigue</td>
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<td></td>
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<td></td>
<td>↑ time in moderate HR zone</td>
</tr>
<tr>
<td>Rowsell et al. (2011)</td>
<td>20</td>
<td>4-day junior soccer tournament</td>
<td>5 x 1 min, CWI (10°C); TWI (34°C)</td>
<td>↓ decline in total distance and high-intensity running performance</td>
<td></td>
</tr>
</tbody>
</table>

↑ = increased; ↓ = reduced; ↔ = no change; ACT = active recovery; CG = compression garments; CHO+STR = carbohydrate and stretching; CK = creatine kinase; CMJ = counter-movement jump; CWI = cold-water immersion; CWT = contrast-water therapy; ECCS = Emergency Cold Containment System; FABP = fatty acid binding protein; GRV = Game Ready Active Cooling Vest; HR = heart rate; LDH = lactate dehydrogenase; IL-1b = interleukin-1b; IL-6 = interleukin-6; IL-10 = interleukin-10; Mb = myoglobin; MS = muscle soreness; MVC = maximal voluntary contraction; NIV = Nike ice-vest; RSA = repeated sprint ability; Tₖ = core temperature; Tₑₑ = rectal temperature; Tₛₖ = skin temperature; TWI = temperate-water immersion.
2.6.3 Post-Exercise Cooling for Recovery of Skill Performance in the Heat

Despite the demonstrated improvements in the rate of physical and physiological recovery achieved with post-exercise cooling (Ranalli et al., 2010; Leeder et al., 2012), consideration for the integrative effects on sports-specific skill performance are lacking. It could be suggested that observed improvements in central and peripheral controls achieved via the removal of high thermal strain might maintain skill performance (Royal et al., 2006). Given the psychomotor deterioration experienced under heat stress (Pilcher et al., 2002), and the return of CNS outflow once elevated $T_c$ have been alleviated (Morrison et al., 2004; Todd et al., 2006), improved physical function after post-exercise cooling might also assist the recovery of skill performance. While involuntary dehydration in cricketers experiencing heat stress (Gore et al., 1993) may reduce acute bowling accuracy (Devlin et al., 2001), it is currently unknown whether faster removal of thermal strain achieved with post-exercise cooling could benefit medium-fast bowling performance in ensuing bouts. Although speculative, the greater maintenance of voluntary force apparent after cold therapy during repeated efforts (Pournot et al., 2011) may also alleviate compensatory motor coordination adopted under fatigue (Enoka & Stewart, 1992) and avoid this higher injury risk (Hopkins et al., 2001; Pietrosimone et al., 2012). For the medium-fast bowler, this might lessen shoulder counter rotation associated with reduced ball accuracy (Portus et al., 2000), or ease lumbo-pelvic rotation, lumbar flexion moments, and thus risk of spondylolysis (Foster et al., 1989; Portus et al., 2004). Nevertheless, these presumptions are largely unfounded and additional study of post-exercise cooling is required in sport-specific scenarios to elucidate their effects on the recovery of technical skill performance.
2.6.4 Mechanisms Related to Performance Improvements via Post-Exercise Cooling

2.6.4.1 Physiological Mechanisms

Traditional models used to explain the ergogenic effects of post-exercise cooling on improved recovery of performance relate to an increased circulatory volume mediated by vasoconstriction at the periphery (Wilcock et al., 2006; Duffield, 2008). Halson and colleagues (2008) highlight cold-water immersion to reduce heart rate by 3 – 15% after a 40 min time trial in 34°C heat. These authors, and others (Yeargin et al., 2006; Vaile et al. 2008a; Vaile et al. 2011), point to the apparent redistribution of blood from the periphery to the core to ease cardiovascular strain through increased venous return, stroke volume and cardiac output. Consequently, improved cardiac efficiency is suggested to increase muscle blood flow, and so improve subsequent performance (Marsh & Sleivert, 1999). This assumption might stand where a greater cardiac output is associated with a lower peripheral resistance to muscle and organ blood flow during temperate water immersion (Epstein et al., 1976; Blyden et al., 1989). However, after post-exercise cooling, this is an unlikely outcome as centralising blood flow increases blood pressure and peripheral resistance (Bonde-Petersen et al., 1992), reducing tissue oxygenation and limb blood flow (Yanagisawa et al., 2007; Gregson et al., 2011; Vaile et al., 2011). While it is common for the reduced cardiovascular strain achieved with cooling to be reported alongside enhanced recovery of exercise performance (Halson et al. 2008; Vaile et al. 2008a; Vaile et al. 2010), specific mechanisms relating to this remain unknown.

A possible explanation is that cold therapy following exercise may improve the restoration of cardiac autonomic function (Stanley et al., 2012). Under normal conditions, the restoration of exercise-induced alterations in autonomic balance (parasympathetic reactivation and
sympathetic deactivation) is indicative of a lower cardiovascular strain following exercise (Seiler & Kjerland 2006). Importantly, cold-water immersion increases parasympathetic recovery after intermittent (Al Haddad et al., 2010) and supra-maximal exercise (Buchheit et al., 2009; Parouty et al., 2010). Buchheit and others (2009) suggest that cold-water immersion (14°C) administered between repeated supramaximal exercise in the heat (35°C) can alleviate reduced vagal nerve activity and heart rate variability indexes by increasing activation of cardiopulmonary baroreceptors. Further, the preservation of dominant cardiac parasympathetic function has in turn been related to sustained training intensity, and improved aerobic power and 10 km run times over an 8 week training period (Buchheit et al., 2010). Nevertheless, it remains unclear whether faster parasympathetic reactivation achieved with post-exercise cooling improves recovery and subsequent performance where repeated bouts are completed on the same day (Buchheit et al. 2009; Stanley et al., 2012). For cricketers accommodating heavy scheduling in the heat, a faster return of cardiac autonomic function may promote a greater ability to maintain training status (Borresen & Lambert, 2008), and in turn might have the potential to influence ensuing athletic performance demands (Buchheit et al., 2010).

2.6.4.2 Neuromuscular Mechanisms

An alternative explanation to traditional cardio-dynamic physiological factors holds that lowered thermal demands achieved via post-exercise cooling in the heat to restore voluntary force and motor unit recruitment (Morrison et al. 2004; Thomas et al. 2006), otherwise suppressed under hyperthermic conditions (Saboisky et al., 2003; Martin et al., 2004). In support of this premise, passive heating/cooling models return voluntary force production and central activation to normal values upon reversal of high internal temperatures (Morrison et
Similar responses seem true for exercise-based models, as Pointon et al. (2012) report higher MVC torque, VA and EMG signalling of the quadriceps immediately after cold-water immersion to correspond with a faster rate of $T_c$ decline. Interestingly though, this improved neuromuscular function of the knee-extensors was not reflected in repeat-sprint ability at the same time point (Pointon et al., 2012). Further, these data contrast with that of Peiffer et al. (2010b), who reported brief (5 min) cold-water immersion (14°C) to demonstrate no effect on neuromuscular properties or recovery of 1 km time trial performance. However, some caution must be advised in interpreting these data as $T_{re}$ and $T_{mu}$ of 37.2°C and 37.7°C after the initial cycling bout are markedly lower than Pointon et al. (2012) ($T_c$ ~39.0°C) and are unlikely to thermally inhibit CNS drive (Peiffer et al., 2010b). Accordingly, it is feasible that centrally mediated mechanisms could regulate performance recovery in relation to thermal load, though current literature is speculative in supporting this notion following exercise in the heat.

One possible premise is that acute concomitant reductions in both thermoregulatory and cardiovascular strain might assist in the maintenance of cerebrovascular regulation, improving cerebral oxygenation, and potentially CNS drive (Nybo & Nielsen, 2001a; Nybo & Rasumussen, 2007). While reductions in cerebral oxygenation during maximal exercise in the heat have been attributed to lower middle cerebral artery blood flow velocity (Nybo et al., 2001b; González-Alonso et al., 2004), increasing central blood volume after hyperthermic exercise through the use of immersion-based cooling techniques would likely counter these perturbations, as mean arterial pressure and cardiac output are improved (Vaile et al., 2011). Although this hypothesis has not been examined from a recovery context, considering the interactions of both $T_c$ (Morrison et al., 2004; Thomas et al., 2006) and cerebral oxygenation in altering central motor output (Amman & Kayser, 2009; Rasmussen et al., 2010), the effects
of cerebrovascular regulation on neuromuscular function after post-exercise cooling warrants further inquiry. Accordingly, where post-exercise cooling has been reported to improve acute recovery of voluntary force and activation after intermittent-sprint exercise in the heat (Pointon et al., 2012), concurrent examination of cerebral blood flow and haemodynamics may improve current understanding of central mechanisms relating to neuromuscular drive (Perrey, 2009; Bourdillon & Perrey, 2012).

Additionally, post-exercise cooling is theorised to treat symptoms of exercise-induced muscle damage, including functional impairment and perceptual soreness associated with strenuous exercise (Howatson & van Someren, 2008). Peripheral vasoconstriction in response to cold therapies reduces cellular permeability, slowing interstitial protein efflux and uptake by the lymphatic system (Eston & Peters, 1999; Enwemeka et al., 2002). This lower diffusion and vesicular transport of fluid to the interstitial space may blunt inflammatory responses to exercise- or heat-induced muscle damage, proposed to ease pain, oedema and strength losses (Meeusen & Lievens, 1986; Smith, 1991; MacIntyre et al., 1995). Eston and Peters (1999) reported cold-water immersion to blunt creatine kinase activity (48 – 72 h) after eccentric loading of the elbow flexors, though no effect on force output was apparent. While increasing the external validity, Bailey and others (2007) also concluded that some indices of muscle damage (soreness and myoglobin concentration) could be alleviated through cold-water immersion when administered after prolonged, intermittent-sprint exercise. Importantly, these authors report declines in isometric MVC force of the knee extensors to be reduced in cold-water immersion trials, demonstrating 9% and 11% higher maintenance of neuromuscular function at 24 and 48 h, respectively. Reduced contractile unit disruption after cold therapy should intuitively improve the rate of return to pre-exercise performance; however, links between biochemical profiles indicative of muscle damage and functional performance are
questionable (Byrne et al., 2004). Regardless, any cooling-induced improvement in neuromuscular recovery may benefit medium-fast bowling performance, particularly during multi-day formats, where competition and training bouts could be scheduled on 5 days in succession.

2.6.4.3 Perceptual Mechanisms

Improvements in subjective ratings of recovery are commonly reported after post-exercise cooling (Halson et al., 2008; Ingram et al., 2009; Rowsell et al., 2009). In particular, cold-water immersion is demonstrated to blunt perceived muscle soreness for 24 – 96 h following exercise (Kuligowski et al., 1998; Yanagisawa et al., 2003; Goodall & Howatson, 2008). Halson and others (2008) demonstrate cold-water immersion administered after a 40 min time trial under heat stress to evoke immediate reductions in muscle soreness and general fatigue, and greater perceptions of physical and mental recovery. Further, cold-water immersion has been reported to benefit general soreness and fatigue within team-sport tournament scenarios, where the maintenance of game-related physical performance has also been highlighted (Montgomery et al., 2008; Rowsell et al., 2009). Wilcock and colleagues (2006) suggest that these favourable effects might relate to cooling-induced reductions in acetylcholine that slows neuronal transmission (Abramson et al., 1966) to reduce the level of pain perception (Washington et al., 2000). While this explanation is conceivable, given that cooling-induced analgesia likely dissipates within 1 – 3 h (Meeusen & Lievens 1986), sustained reductions in muscle soreness are more likely related to a blunted muscle damage response (Eston & Peters, 1999). Even withstanding any maintenance in neuromuscular function, post-exercise cooling appears to improve perceptual recovery, potentially translating to continued
performance for cricketers where multi-session and multi-day training/competition scheduling is the norm.

Of equal consideration, the reported subjective effects of a placebo effect may improve exercise performance where participants believe they have received beneficial treatment (Beedie & Foad, 2009). Indeed, where improvements in subjective measures of muscle soreness and recovery have been reported, the inability to truly incorporate a placebo control restricts the treatment effect from being ignored (Bailey et al. 2007; Halson et al. 2008; Rowsell et al. 2009). Rowsell and colleagues (2009) highlight all participants undertaking cold-water immersion to report perceivably favourable effects on recovery. Notably, Buchheit et al. (2009) also reported improved subjective recovery with cold-water immersion compared with passive recovery seated in 35°C environmental chamber (6.1 ± 2.1 vs. 4.5 ± 2.0; \( P < 0.01 \)). However, these authors observed no interaction or condition effects between recovery interventions on repeated supramaximal cycling bouts (cold-water immersion: 80.2 ± 3.4 and 81.5 ± 3.2 s vs. control: 80.1 ± 3.2 and 81.2 ± 3.5 s; \( P > 0.05 \)) (Buchheit et al., 2009). While the benefits of a placebo effect in clinical settings are documented (Turner et al., 1994), interpretation of this concept is complicated by increased physiological and psychological strain following exercise (Beedie, 2007). Potential influences of a placebo effect may be particularly evident in cricket, whereby current use of post-exercise cooling requires considerable buy-in from the athlete for sustained adherence to occur. Finally, although the contributing factors relating to an improved subjective recovery remain to be elucidated, the current literature is limited by the predominant use of two-condition experimental designs, which is unable to demonstrate the effects of post-exercise cooling relative to baseline (Beedie, 2007).
2.7 The Effect of Cooling Methodology

2.7.1 Cold-Water Immersion

Scheduling and location of elite competition in thermally challenging environments has increased interest in cooling interventions for the maintenance of acute and repeated efforts (Ranalli et al., 2010; Leeder et al., 2012; Wegmann et al., 2012). Whole-body cold-water immersion is reported as being particularly effective in removing heat load (Casa et al., 2007), though part-body cooling may also improve thermal strain and exercise performance when applied to the head (Ansley et al., 2008), neck (Tyler et al., 2010), torso (Arngrímsen et al., 2004), quadriceps (Castle et al., 2006), hands (Grahn et al., 2005) and feet (Hagobian et al., 2004). Unfortunately, direct comparison of whole-body cold-water immersion and part-body methods is lacking, and where included, clear findings may be limited by the type of exercise assessment (Castle et al., 2006) and the level of physiological strain incurred (King & Duffield, 2009). Nevertheless, it seems that effect of body cooling may be mode specific, with greater benefits achieved in repeated aerobic performance (4.25%) compared with anaerobic exercise bouts (0.66%) (Ranalli et al., 2010).

Although the direct comparison of cold-water immersion and alternate cooling methods in performance trials are lacking (Castle et al., 2006; King & Duffield, 2009), collective interpretation of rates of heat removal may offer insight to potential benefits of various cooling techniques for athletes experiencing heat strain (Casa et al., 2007; Ranalli et al., 2010). It is suggested that marked physiological perturbations must be incurred via both exertional/environmental heat gain and cooling-induced heat loss for changes in performance outcomes to be achieved (Duffield & Marino, 2007). Yeargin et al. (2006) and Vaile et al. (2008b) show 14°C cold-water immersion to reduce elevated $T_c$ after exercise in the heat by
0.08 and 0.05°C min\(^{-1}\) during 12 and 15 min interventions, respectively. Equally, while pre-cooling via cold-water immersion (10°C) may not reduce mean body temperatures during the intervention period (Duffield et al., 2010), lowered T\(_c\) after 30 min (cold-water immersion: 37.93 ± 0.36°C vs. control: 38.50 ± 0.80°C; \(P < 0.05\)) represents an increased heat storage capacity and higher thermal control during exercise (Skein et al., 2012). Further, when compared against alternate methods (fanning (22°C): 0.03°C min\(^{-1}\); ice packs: 0.04°C min\(^{-1}\); hand cooling device: 0.06°C min\(^{-1}\)), cold-water immersion demonstrates the most efficient heat losses (Casa et al., 2007). The dosage effects of cooling are well noted (Proulx et al., 2003; Castle et al., 2006; Bogerd et al., 2010); however, given the 24-fold greater thermal conductivity of water compared to air (Toner & McArdle, 2011), these higher rates of heat transfer are not surprising. Accordingly, cold-water immersion may offer the greatest cooling stimulus, though issues relating to practicality (cost of permanent infrastructure), logistics (timing and administration in team settings) and environmental concerns (water quality and quantity) can restrict field-based use (Barwood et al., 2009; Duffield et al., 2009d).

### 2.7.2 Field-Based Application

While the efficacy of cold-water immersion cooling for the protection and recovery of exercise and environment-induced heat stress is clear (Ranalli et al., 2010; Wegmann et al., 2012), the external validity of this method remains questionable (Barwood et al., 2009; Duffield et al., 2009). During non-catastrophic scenarios, practical considerations for implementation must be balanced with an effective cooling stimulus to ensure logistical constraints do not interrupt other commitments (pre-match routines, team meetings, coach discussions) that may also have relevance for ensuing performance (DeMartini et al., 2011). Enhancing the ease of use for pre- or post-session cooling through the implementation of
multiple, largely portable, part-body methods have been previously reviewed (Duffield, 2008; Ranalli et al., 2010), though in isolated use have demonstrated only small and/or conflicting results (Arngrímsson et al., 2004; Duffield & Marino, 2007). Duffield and Marino (2007) highlight minimal thermoregulatory ($T_c$, $T_sk$, and HR; $P > 0.05$; $d= 0.3 – 0.5$) or performance benefits (15 m sprint times and self-paced running distances; $P > 0.05$) attained via a 15 min ice-vest pre-cooling and 10 min mid-exercise reapplication in 32°C heat. Contrastingly, Arngrímsson et al. (2004) demonstrated ice-vest use during a 38 min active warm-up to improve ensuing 5 km run time by 1.1% ($P < 0.05$); the equivalent of a 57 m advantage when calculated at the average speed run compared to control. Such divergent findings might be explained by the lesser surface area coverage (Daanen et al., 2006), duration (Duffield, 2008) and cooling intensity (Bogerd et al., 2010) of part-body techniques. However, it is feasible these concerns related to cooling stimulus may be alleviated through the use of the addition of multiple part-body methods in conjunction to maximise the dosage effects, while maintaining external validity for use in the field (Quod et al., 2008; Duffield et al., 2009d; Ross et al., 2011).

Several groups report the benefits of ice-vests supplementing cold-water immersion before exercise in the heat (Duffield & Marino, 2007; Quod et al., 2008; Ross et al., 2011). While this strategy may assist to extend thermoregulatory control, concerns relating to a reliance on permanent infrastructure and high water quality, especially when travelling, are largely unavoidable. The methods of Duffield and colleagues (2009d) overcome this constraint via a mixed-method pre-cooling procedure that included the use of an ice-vest, cold, wet towels worn around the neck and shoulders, and ice bags positioned on upper leg. Importantly, the authors showed this manoeuvre to blunt mean $T_c$ responses ($38.8 \pm 0.3 \text{ vs. } 39.3 \pm 0.4°C$; $P < 0.05$), and increase total running distances completed ($3.35 \pm 0.20 \text{ vs. } 3.11 \pm 0.13 \text{ km}; P <$
0.05) (Duffield et al., 2009d). Similarly, Barwood and others (2009) examined the effects of commercially available air cooling, liquid cooling and chemical phase change materials with simple hand-immersion and whole-body fanning during a simulated 15 min half time break. Most pertinent, these data showed practical and cost-effective whole-body fanning to be most effective in maintaining thermal control and completing greater self-paced treadmill running before reaching a $T_{re}$ of 38.5°C. Accordingly, while cold-water immersion may represent the ‘gold standard’, best practice in field-based settings under heat stress may also include whole-body mixed-method and fanning interventions that offer an effective means of cooling within the logistical constraints of the team sport environment. These data have particular relevance for cricket-specific scenarios and may support the efficacy of portable mixed-method cooling strategies for use where insufficient water quality/quantity and ice-bath facilities are available. Nevertheless, no data has been reported on any cold-water immersion or mixed-method cooling technique and how such methods may influence the performance and recovery of medium-fast bowling is unknown.

### 2.8 Summary

High ambient temperatures present a constant challenge for medium-fast bowlers, as elevated thermal strain decreases skill performance (Devlin et al., 2001) and increases risk of heat-related illness (Driscoll et al., 2008; Finch & Boufous, 2008). Where the down-regulation of neuromuscular recruitment and pacing may assist to protect physiological homeostasis (Tucker, 2009), this phenomenon will likely impair performance, as maximal momentum and summation of segmental velocities during the bowling action are imperative for ball speed (Glazier et al., 2000; Salter et al., 2007). The use of cooling interventions pre- and/or post-exercise could enhance thermoregulatory control to maintain performance and improve
physiological and perceptual recovery. While this may be best achieved via cold-water immersion (Casa et al., 2007), the external validity of this method within a team environment is questionable (Marino, 2002), particularly when travelling in many cricket playing countries. Accordingly, alternate part-body and mixed-method cooling techniques may offer enhance practicality for field-based use (Barwood et al., 2009; Duffield et al., 2009d). To date, no data have been reported on the effects of pre- or post-exercise cooling techniques on the performance or recovery of medium-fast bowlers in the heat. Collectively, interpretations of the above literature implicate central, peripheral and perceptual contributions to exercise performance and recovery in the heat, though further insight into how these mechanisms might be altered using practical cooling methods in relation to cricket fast bowling is required.
Volume-Dependent Response of Pre-Cooling for Intermittent-Sprint Exercise in the Heat

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Abstract

This study examined the effects of pre-cooling volume on neuromuscular function and performance in free-paced intermittent-sprint exercise in the heat. Ten male, team-sport athletes completed four randomised trials involving an 85-min free-paced intermittent-sprint exercise protocol in 33°C ± 33% relative humidity. Pre-cooling sessions included whole body (WB), head+hand (HH), head (H) and no cooling (CONT), applied for 20 min pre-exercise and 5 min mid-exercise. Maximal voluntary contractions (MVC) were assessed pre- and post-intervention and mid- and post-exercise. Exercise performance was assessed with sprint times, % decline and distances covered during free-paced bouts. Measures of core (T_c) and skin (T_sk) temperatures, heart rate, perceptual exertion and thermal stress were monitored throughout. Venous and capillary blood was analysed for metabolite, muscle damage and inflammatory markers. WB pre-cooling facilitated the maintenance of sprint times during the exercise protocol with reduced % decline (P= 0.04). Mean and total hard running distances increased with pre-cooling 12% compared to CONT (P < 0.05), specifically, WB was 6 – 7% greater than HH (P= 0.02) and H (P= 0.001) respectively. No change was evident in mean voluntary or evoked force pre- to post-exercise with WB and HH cooling (P > 0.05). WB and HH cooling reduced T_c by 0.1 – 0.3°C compared to other conditions (P < 0.05). WB T_sk was suppressed for the entire session (P= 0.001). HR responses following WB cooling were reduced (P= 0.05; d= 1.07) compared to CONT conditions during exercise. A relationship between pre-cooling volume and exercise performance seems apparent, as larger surface area coverage augmented subsequent free-paced exercise capacity, in conjunction with greater suppression of physiological load. Maintenance of MVC with pre-cooling, despite increased work output suggests the role of centrally-mediated mechanisms in exercise pacing regulation and subsequent performance.
Introduction

Hot and humid conditions compound the physiological strain of increased metabolic heat production associated with exercise, whilst reducing avenues for heat dissipation to the surrounding environment (Nybo, 2008). Accordingly, both physiological and behavioural responses control the rise in thermoregulatory load, often to the detriment of exercise performance (Wendt et al., 2007). These noted responses may be particularly pertinent for team-sport athletes competing in warm environments, owing to increased thermal loads associated with intermittent-sprint activity compared to continuous modes at matched intensities (Ekblom et al., 1971; Cable & Bullock, 1996). Given the observed exacerbated loads and reduced performances in the heat, the popularity of pre-cooling has increased as team-sport athletes seek to counter the reduction of exercise performance in the heat.

A large quantity of laboratory-based research supports the efficacy of pre-cooling for endurance exercise performance in the heat (Marino, 2002; Quod et al., 2006; Duffield, 2008). Regardless of traditionally equivocal findings (Marino, 2002; Quod et al., 2006; Duffield, 2008), more recent studies of prolonged intermittent-sprint exercise following pre-cooling demonstrate ergogenic benefits (Castle et al., 2006), particularly in the maintenance of self-paced sub-maximal work (Duffield & Marino, 2007; Duffield et al., 2009d). Typically, whole body methods utilising cold micro-climates, specifically water immersion or cold air, can result in improved exercise performance and/or reductions in thermoregulatory strain (Marino, 2002; Quod et al., 2006; Duffield, 2008). Despite wide support (Duffield, 2008), whole body cold-water immersion may provide environmental and logistical concerns surrounding their field-based application, resulting in problematic (water access) and/or impractical (cooling a full team) implementation (Marino, 2002). Recently, the dosage effect
demonstrated when comparing whole- versus part-body cooling methods (Castle et al., 2006; Daanen et al., 2006; Duffield & Marino, 2007) has provoked interest in combining multiple part-body techniques, thus maintaining surface area coverage and enhancing the practicality of pre-cooling (Quod et al., 2008; Duffield et al., 2009d). However, the explicit effect of the volume of the imposed cooling stimulus necessary for optimal physiological, metabolic and performance outcomes remains equivocal.

Augmented heat storage capacity following pre-cooling aids in the suppression of increased thermoregulatory load associated with exercise in the heat (Marino, 2002). Whilst related reductions in heart rate along with skin and/or core temperature may indicate the maintenance of central blood volume (González-Alonso et al., 2008), the mechanisms of pre-cooling may relate to the role of higher central regulation (Nybo & Nielsen, 2001a). Elevated core temperature impairs CNS motor drive, consequently reducing neuromuscular recruitment, force output and voluntary activation (Kay et al., 2001; Nybo & Nielsen, 2001a; Morrison et al., 2004; Todd et al., 2005). Hence, blunting the rise in core temperature by pre-cooling may lead to better pacing during self-paced exercise (Kay et al., 1999; Kay et al., 2001; Duffield et al., 2010). Further, the reduction in thermoregulatory and/or physiological load may also ease generic stress responses relating to alterations in metabolic processes (Febbraio, 2001) and elevated damage and inflammatory markers following exercise in the heat (Alzeer et al., 1997). As such, the cause-effect relationship and underlying mechanisms of the imposed pre-cooling stimulus requires further attention to provide insight as to the mechanisms on neuromuscular function which might improve exercise in the heat and also allow for the development of ecologically valid, evidence-based cooling techniques.
Whilst the rationale for pre-cooling athletes for the protection of acute exercise performance in the heat is accepted (Marino, 2002; Quod et al., 2006; Duffield, 2008), practical limitations may restrict the application of whole body immersion techniques in the field. Mixed-method approaches to pre-cooling demonstrate advantageous effects on exercise performance, physiological loads and perceptual state (Quod et al., 2008; Duffield et al., 2009d). However, a lack of data exists to demonstrate the optimal volume of cooling stimulus necessary for ergogenic benefit. Moreover, apparent influences of pre-cooling on CNS activity and subsequent self-selected work output require further investigation. Therefore, the purpose of this study was to determine the effects of pre-cooling volume on free-paced intermittent-sprint performance and physiological responses in heat stress. A complementary aim was to determine the effects of pre-cooling on voluntary force and evoked twitch properties and their relationship to exercise performance in the heat.

**Methods**

**Participants**

Ten, well trained, male team-sport athletes (mean ± SD: age 20.9 ± 2.6 y; height 182.1 ± 8.8 cm; body mass 77.8 ± 6.7 kg; body surface area 1.98 ± 0.12 m²) volunteered to participate in this study. Participants regularly competed in regional level team-sport competitions (cricket, rugby union) and reported ≥ 3 training days per week including sports specific skill-based and strength and conditioning sessions. Following disclosure of all risks and benefits, all participants provided verbal and written consent prior to the commencement of all testing procedures. Experimentation was approved by the Ethics in Human Research Committee of the University.
Overview

A randomised, repeated measures cross-over design was used to determine the effects of pre-cooling volume on performance, physiological, biochemical and perceptual responses to an intermittent-sprint exercise protocol. The study was conducted as part of a series of cricket related studies and hence the exercise protocol was based on fast bowling specific intermittent-sprint exercise (Petersen et al., 2010b); but, was adapted to increase the volume of work required to allow reporting of a more generic protocol for team-sport activity as previously suggested (Duffield & Marino, 2007). An initial equipment and procedural familiarisation session was performed before commencing data collection. This included completion of the entire exercise protocol in hot conditions, application of neuromuscular assessments and cooling techniques. Testing sessions were standardised for each participant and separated by 5-7 days to allow full recovery. Physical activity, diet and fluid intake were all documented in food and physical activity diaries in the 24 h prior to the first testing session and replicated for the following sessions. Participants were educated on keeping dietary and workload records, with standardisation compliance qualitatively assessed prior to commencement of each session. Sessions were conducted on an enclosed 20 m synthetic running track in hot conditions (33.0 ± 0.7°C and 33.3 ± 3.9% relative humidity). Environmental temperatures were controlled by a customised gas heating system and four electronic 2,000 W room heaters (Kambrook, Port Melbourne, Australia) positioned at 5 m increments alongside the running track. All testing sessions were identical so that pre-cooling volume was the only manipulated variable throughout. Participants performed five sessions including a familiarisation session, control session (no pre-cooling), head cooling session (pre-cooling with an iced towel), head and hand cooling session (pre-cooling with an iced towel and container of cold water) and a mixed-method whole body session (pre-cooling with iced towel, container of cold water, ice vest and ice packs applied to the quadriceps).
Participants were required to abstain from strenuous exercise and alcohol 24 h before and all caffeine and food substances 3 h before each testing session. A standardised volume of water (500 mL) was consumed 1 h pre-exercise to regulate hydration status.

**Exercise protocol**

Participants performed an intermittent-sprint running protocol comprising of 2 x 35 min spells of exercise (Spell 1 and 2), separated by a 15 min recovery period on the enclosed 20 m running track. Prior to commencement, a 5 min warm-up period was completed in hot conditions involving 20 m shuttle running with increments in running speed each minute and 6 repeated 15-m maximal sprints. The 2 x 35 min exercise protocol consisted of 10 (2 x 5) bouts of 6 x 15 m maximal sprint efforts separated by 5 min bouts of self-paced activity at different intensities; designed to incorporate the movement requirements for cricket fast bowlers (Petersen et al., 2010b). Participants performed a set of 6 x 15 m sprints commencing at 30 s intervals, emulating a 6-ball cricket over. During the 5 min interval between sets of sprints, participants performed 1 min periods of self-paced, sub-maximal exercise, including walking, jogging and hard running (Duffield & Marino, 2007). Participants were informed of the required intensity on a minute by minute basis. Self-paced, sub-maximal activity was performed on the 15 m running track in a shuttle run fashion and participants were requested to return to the starting position at 50 s of each self-paced minute to then commence the subsequent intensity. Each data collection session involved 10 sets of (6) sprints and 8 periods of 5 min self-paced sub-maximal running bouts, thus incorporating the demands of 2 x 5 over spells of fast bowling. Participants were offered verbal support and encouragement throughout to cover the greatest distance during the hard running bouts, and jog or walk at a self-selected pace during the respective jogging and walking bouts. All fluid consumption
was restricted throughout the exercise protocol. Previously collected but unpublished reliability data demonstrate the Intra-Class Correlation of mean sprint times, self-paced distances and hard running distances covered was $r= 0.94 – 0.98$, while the Technical Error of Measurement was $0.5 – 2\%$ and Co-efficient of Variation was $0.6 – 2\%$.

**Pre-cooling intervention**

Following all resting measures, a pre-cooling intervention was performed for 20 min pre-exercise and for 5 min during the 15 min mid-session recovery period. In order to induce a volume effect, a step-wise approach to part-body cooling was used, with pre-cooling sessions involving no cooling (control), head cooling (H), head+hand cooling (HH), or mixed-method whole body cooling (WB). During the H cooling session, participants were cooled using an iced towel soaked in water ($5.0 \pm 0.5\degree C$) prior to being placed over the head and neck. HH cooling was achieved using an iced towel ($5.0 \pm 0.5\degree C$) covering the head and neck whilst each hand was immersed up to the wrist in separate containers of cold water actively maintained at $9.0 \pm 0.5\degree C$. During the WB cooling session, participants were cooled with an iced towel over the head and neck, hands immersed to the wrist in cold water, ice-vest covering the torso (Arctic Heat, Brisbane, Australia) and frozen ice-packs applied to the quadriceps (Techni Ice, Frankston, Australia). Ice-vests and ice-packs were stored at $-20\degree C$ prior to and following use. The mixed-method approach was selected based on the practical ease and portability of equipment compared to cold water immersion (Duffield et al., 2009d).

No cooling stimulus was applied during the control condition (CONT). Standardised warm-up procedures commenced immediately following neuromuscular assessment, approximately 5 min post-intervention completion. Reapplication of cooling methods during the mid-exercise recovery period occurred within approximately 10 min to accommodate the
collection of neuromuscular and biochemical measures. All treatments were performed in a seated position within controlled laboratory conditions of 33°C and 33% relative humidity. Percentage surface area volumes covered during pre-cooling were estimated at 10%, 15% and 35% for H, HH and WB trials respectively (Lee & Choi, 2009).

Measures

Performance

Exercise performance was determined by 15 m sprint time and distance covered throughout sub-maximal exercise bouts. An infra-red timing system (Speed-Light, Swift, Wacol, Australia) was used to record sprint times, whilst % decrement was calculated according to Dawson et al. (1993). Incremental 1 m markings along the 15 m synthetic running track allowed for calculation of distances covered during each individual sub-maximal exercise bout. Participants wore personal athletic training attire (T-shirt, shorts, socks and running shoes) that were standardised throughout. Data were reported as mean or total for individual exercise modes (walk, jog and hard run).

Neuromuscular

Measures of voluntary force and evoked twitch properties of the right knee extensors were assessed pre-intervention, post-intervention, mid-exercise and post-exercise using an isokinetic dynamometer (Kin-Com, Model 125, Chattanooga Group Inc., Hixon, USA) connected to a host computer and customised software (v8.0, LabVIEW; National Instruments, North Ryde, Australia). Participants were seated in an upright position, with the axis of rotation of the dynamometer visually aligned with the lateral femoral epicondyle and
the lower leg attached to the lever arm 1 cm above lateral malleolus on the right leg. Seating posture was standardised with the knee and hip positioned at 90° flexion (0° represents full extension) and securely fastened to the dynamometer using conventional waist and shoulder straps. Supra-maximal transcutaneous electrical stimulation of the femoral nerve was administered via a reusable gel adhesive electrode (diameter 10 mm; MEDI-TRACE™ Mini 100 Pediatric Foam Electrodes, Covidien, Mansfield, USA) located on the anterior thigh 3 cm below the inguinal fold. An additional reusable gel adhesive electrode (90 x 50 mm; Verity Medical Ltd., Stockbridge, England) positioned on the medio-posterior aspect of the upper thigh below the gluteal fold acted as the anode. A single square-wave pulse with a width of 200 µs (400 V with a current of 100-450 mA) was delivered by a Digitimer DS7 stimulator (Digitimer Ltd., Welwyn Garden City, England) connected to a BNC2100 terminal block and signal acquisition system (PXI1024; National Instuments, Austin, USA). Peak twitch force was detected with incremental increases in stimulus intensity and final levels were amplified by 10% to ensure attainment of supramaximal stimulation. Five pulses separated by 20 s were delivered in a rested state to assess resting evoked twitch properties. Subsequently, participants completed a maximal voluntary contraction (MVC) protocol involving 5 x 5 s isometric trials using a work to rest ratio of 1:6. The MVC was defined as the mean peak torque value attained during voluntary contractions. A superimposed twitch was manually triggered during each MVC within 1 – 2 s after commencement to coincide with an observed plateau in peak torque. An additional stimulus was delivered to the resting muscle immediately post-contraction to calculate potentiated twitch properties. Voluntary activation (VA) was determined using the twitch interpolation technique (Allen et al., 1995). Time to peak torque (TPt) was calculated using the time from evoke force onset to peak potentiated twitch torque. Analyses of neuromuscular data were performed using MATLAB software (R2009b 7.9.0.529, The Mathworks Inc., Natick, USA).
Physiological measurements

Pre- and post-exercise toweled dry measures of nude body mass were recorded using calibrated scales (HW 150 K, A & D, Thebarton, Australia) to estimate sweat loss. A mid-stream urine sample was collected pre-exercise to assess urine specific gravity (USG; Refractometer 503, Now. Nippon Optical, Works Co, Tokyo, Japan). Heart rate was measured using a chest transmitter and wrist watch receiver (FS1, Polar Electro Oy, Finland) at 5 min intervals during respective intervention and exercise protocols. Core temperature ($T_c$) was measured using a telemetric capsule (VitalSense, Mini Mitter, Bend, USA), ingested at a standardised 5 h pre-exercise to ensure passing into the gastrointestinal tract. The $T_c$ was measured pre-intervention and at 5 min intervals throughout the cooling intervention and exercise protocol, respectively. For detailed discussion of the reliability (ICC= 0.99) and validity ($r= 0.98$) of ingestible $T_c$ capsules see Gant and colleagues (2006). Skin temperatures ($T_{sk}$) were assessed at the sternum, mid-forearm, mid-quadriceps and medial calf by an infra-red thermometer (ThermoScan 3000, Braun, Germany) at 5 min intervals during the pre-cooling intervention, mid-protocol break and post-exercise. This technique has been reported to be a reliable (ICC= 0.96) and valid ($r= 0.92$) measure of $T_{sk}$ (Burnham et al., 2006). Mean $T_{sk}$ was calculated according to Ramanathan (1964).

Blood collection and biochemical analysis

A 100µL pre-exercise sample of capillary blood was collected from a hyperaemic earlobe to measure pH, glucose, lactate [$La^-$] and bicarbonate ($HCO_3^-$) (ABL825 Radiometer, Copenhagen, Denmark). Additional capillary blood samples were collected mid-exercise and immediately post-exercise. To determine the effects of pre-cooling on muscle damage, inflammation and generic stress responses, venous blood was collected from an antecubital
vein pre- and 30 min post-exercise and analysed for creatine kinase (CK), C-reactive protein (CRP), testosterone (TEST), cortisol (CORT) and insulin (INS). Using an evacuated venipuncture system and serum separator tubes (Monovette, Sarstedt, Numbrecht, Germany), samples were allowed to clot at room temperature prior to centrifugation for 10 min at 4000 rpm. Supernatant was then extracted and stored at -20°C until analysis. Before analysis the serum was allowed to reach room temperature and mixed via gentle inversion. CK and CRP were analysed according to manufacturer’s instructions provided in the respective assay kits (Dimension Xpand spectrophotometer, Dade Bearing, Atlanta, USA). CK concentrations were determined using an enzymatic method and bichromatic rate technique. CRP samples were manually diluted according to manufacturer’s instructions and analysed with the particle enhanced turbidimetric immunoassay technique (PETIA). INS, TEST and CORT levels were detected using a solid-phase, competitive chemiluminescent enzyme immunoassay (Immulite 2000, Diagnostic Products Corp., Los Angeles, USA). To avoid inter-assay variations, all samples for each subject were analysed in the same assay run. Intra-assay Coefficients of Variance were < 5% for all venous blood analyses. Serum hormone concentrations were not corrected for plasma volume shifts, thus all statistical analyses were performed on hormone values based on actual measured circulating concentrations.

**Perceptual Measures**

Rating of perceived exertion (RPE) and thermal sensation scale (TSS) were recorded at 5 min intervals throughout pre-cooling and exercise protocols. RPE was determined according to the Borg CR-10 scale, where ranking ranged from 0 (nothing at all) to 10 (maximal). TSS was assessed using an 8-point Likert scale, ranging from 0 (unbearably cold) to 8 (unbearably hot).
Statistical analysis

Data are reported as mean ± standard deviation (SD). A repeated-measures ANOVA was performed to detect within treatment differences. Unprotected pairwise comparisons (Protected Fisher’s LSD) were applied to determine the source of significance, which was accepted when \( P \leq 0.05 \). Analysis was performed using the Statistical Package for Social Sciences (SPSS v 16.0, Chicago, USA). Standardised effect sizes (ES; Cohen’s d) analyses were used in interpreting the magnitude of differences between conditions. An ES was classified as trivial (<0.20), small (0.20-0.49), moderate (0.50-0.79) or large (>0.80).

Results

Performance

Mean and peak ± SD speed and % decline in speed for Spell 1 and Spell 2 respectively are presented in Table 3.1, whilst mean ± SD individual sprint times are presented in Figure 3.1A. No significant differences were detected between cooling procedures for mean sprint times or peak sprint speeds during Spell 1 or Spell 2, respectively (\( P = 0.08 – 0.91 \)). Large ES indicated faster mean sprint times with WB (\( d = 0.94 \)) and HH cooling (\( d = 1.07 \)) compared to CONT during Spell 2. The % decline during Spell 2 was attenuated with WB cooling compared to control (\( P = 0.04 \)). Large ES were apparent for a smaller % decline during Spell 1 in H (\( d = 0.92 \)), HH (\( d = 1.26 \)) and WB (\( d = 0.87 \)) compared with CONT conditions.

Results for mean and total distance covered during sub-maximal exercise bouts including hard running, jogging and walking are presented in Table 3.1. Mean ± SD individual self-paced hard running efforts are presented in Figure 3.1B. Overall, total distances accumulated
were significantly higher with WB (4833 ± 380 m) and HH cooling (4644 ± 360 m) compared to H (4602 ± 448 m) and CONT conditions (4413 ± 545 m), respectively (P= 0.001 – 0.04; d= 0.70 – 1.26). No significant differences and moderate ES continued a dose-response effect between remaining total distance comparisons (P= 0.06 – 0.12; d= 0.53 – 0.72). Significant differences and large ES data indicated greater mean and total distances covered in the WB condition for hard running compared to CONT (P= 0.001; d= 1.49), H (P= 0.001; d= 0.86) and HH cooling (P= 0.02; d= 0.83) conditions. There were also significant increases in hard running distances in a dose-response fashion following H (P= 0.02; d= 0.62) and HH cooling (P= 0.001; d= 0.81) compared to the CONT. Moreover, a significantly increased mean and total hard running completed in Spell 1 was observed with HH cooling data compared to CONT (P= 0.01). Similarly, Spell 2 H (P= 0.04) and HH sessions (P= 0.00; d= 0.87) resulted in significantly higher mean and total hard running work completed compared with CONT, whilst still less than WB cooling.

There were significant increases in mean and total jogging distances covered during Spell 1 and Spell 2 in WB (P= 0.03 and 0.02) and HH sessions (P= 0.01 and 0.01) compared with CONT. Greater mean and total values for jogging distances covered were evident between WB and H cooling sessions during Spell 1 (P= 0.02). No other significant differences were noted among conditions for all remaining mean and total distances for jogging or walking variables during Spell 1 and Spell 2 (P= 0.08 – 0.88).
Figure 3.1. A Mean ± SD individual 15-m sprint times (s) for Whole Body, Head + Hand, Head and Control conditions. B Mean ± SD individual hard running distances (m) covered across for Whole Body, Head + Hand, Head and Control conditions.
Table 3.1. Mean ± SD sprint time variables and sub-maximal running distances covered per session for Whole Body, Head + Hand, Head and Control conditions.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Control</th>
<th>Head</th>
<th>Head+Hand</th>
<th>Whole Body</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sprint time variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Spell 1 sprint (s)</td>
<td>2.63 ± 0.06</td>
<td>2.61 ± 0.08</td>
<td>2.60 ± 0.07</td>
<td>2.61 ± 0.11</td>
</tr>
<tr>
<td>Mean Spell 2 sprint (s)</td>
<td>2.72 ± 0.13</td>
<td>2.66 ± 0.09</td>
<td>2.64 ± 0.08&lt;sup&gt;1&lt;/sup&gt;</td>
<td>2.65 ± 0.09&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Spell 1 decline (%)</td>
<td>6.29 ± 2.10</td>
<td>4.91 ± 2.14&lt;sup&gt;1&lt;/sup&gt;</td>
<td>4.44 ± 2.04&lt;sup&gt;1&lt;/sup&gt;</td>
<td>5.00 ± 2.09&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Spell 2 decline (%)</td>
<td>7.74 ± 4.49</td>
<td>7.18 ± 4.40</td>
<td>6.22 ± 3.87</td>
<td>5.69 ± 3.39&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Sub-maximal running distances</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Spell 1 hard run (m)</td>
<td>153.3 ± 19.7</td>
<td>158.7 ± 18.4</td>
<td>161.4 ± 12.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>168.9 ± 16.2&lt;sup&gt;abc12&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean Spell 2 hard run (m)</td>
<td>140.5 ± 21.8</td>
<td>152.1 ± 20.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>152.6 ± 17.2&lt;sup&gt;21&lt;/sup&gt;</td>
<td>163.5±17.6&lt;sup&gt;abc123&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean Spell 1 jog (m)</td>
<td>102.0 ± 14.9</td>
<td>103.3 ± 13.5</td>
<td>104.6 ± 11.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>107.6 ± 11.2&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean Spell 2 jog (m)</td>
<td>94.1 ± 18.4</td>
<td>99.8 ± 14.8</td>
<td>99.5 ± 13.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>100.7 ± 11.1&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mean Spell 1 walk (m)</td>
<td>63.3 ± 4.5</td>
<td>62.4 ± 6.9</td>
<td>64.1 ± 7.3</td>
<td>64.1 ± 6.4</td>
</tr>
<tr>
<td>Mean Spell 2 walk (m)</td>
<td>59.9 ± 9.3</td>
<td>60.5 ± 8.3</td>
<td>60.6 ± 7.4</td>
<td>62.8 ± 6.1</td>
</tr>
<tr>
<td>Total Spell 1 hard run (m)</td>
<td>1226.7 ± 157.1</td>
<td>1269.7±147.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1291.1±101.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1351.3±129.9&lt;sup&gt;abc12&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total Spell 2 hard run (m)</td>
<td>1124.3 ± 174.7</td>
<td>1216.6 ± 165.5</td>
<td>1220.7±137.6&lt;sup&gt;21&lt;/sup&gt;</td>
<td>1308.2±141.0&lt;sup&gt;abc123&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total Spell 1 jog (m)</td>
<td>816.2 ± 119.4</td>
<td>826.0 ± 108.3</td>
<td>837.0 ± 94.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>860.6 ± 89.9&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total Spell 2 jog (m)</td>
<td>753.1 ± 147.0</td>
<td>798.0 ± 118.3</td>
<td>796.2 ± 108.2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>805.7 ± 88.6&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total Spell 1 walk (m)</td>
<td>253.3 ± 18.1</td>
<td>249.4 ± 27.8</td>
<td>256.3 ± 29.1</td>
<td>256.3 ± 25.7</td>
</tr>
<tr>
<td>Total Spell 2 walk (m)</td>
<td>239.7 ± 37.4</td>
<td>242.1 ± 33.1</td>
<td>242.2 ± 29.4</td>
<td>251.0 ± 24.5</td>
</tr>
</tbody>
</table>

<sup>a</sup> Significant difference compared to Control condition (P < 0.05).
<sup>b</sup> Significant difference compared to Head condition (P < 0.05).
<sup>c</sup> Significant difference compared to Head + Hand condition (P < 0.05).
<sup>1</sup> Large ES (d > 0.8) compared to Control condition.
<sup>2</sup> Large ES (d > 0.8) compared to Head condition.
<sup>3</sup> Large ES (d > 0.8) compared to Head + Hand condition.
**Physiological responses**

Significant reductions and large ES were apparent for $T_c$ (Figure 3.2A) at the end of the intervention period for WB ($P= 0.03; d= 1.62$) and HH cooling sessions ($P= 0.04; d= 1.37$) compared with H. Similarly, $T_c$ was reduced (Figure 3.2A) at the end of the intervention period for WB ($P= 0.003; d= 1.72$) and HH cooling sessions ($P= 0.04; d= 1.46$) compared to CONT. This trend was maintained throughout, with large ES ($d= 0.82 – 1.41$) indicative of a reduced $T_c$ following WB cooling. Significant reductions in $T_c$ with HH cooling compared to CONT were also noted during the protocol ($P= 0.01; d= 0.85$). In comparison with the WB method, $T_c$ response for H cooling and CONT was elevated during the exercise protocol ($d= 0.85 – 1.41$). Finally, HH cooling did not differ from the H cooling condition; rather was increased compared to the WB cooling specifically between the 10th – 35th ($d= 0.81 – 1.19$) and 80th – 85th min ($d= 0.81 – 0.85$). Significant differences and large ES indicated a lower $T_{sk}$ throughout the WB intervention period ($P= 0.001; d= 2.54 – 4.62$) compared to all other conditions (Figure 3.2B). Large reductions in $T_{sk}$ were also apparent for H ($d= 1.00 – 1.85$) and HH cooling sessions ($d= 0.99 – 1.74$) during the intervention period compared to CONT. During the exercise protocol, WB cooling resulted in a reduced $T_{sk}$ compared to all other conditions ($P= 0.001 – 0.03; d= 1.02 – 5.71$); however $T_{sk}$ did not differ between any other conditions. Significant differences and large ES data indicated a lower HR post-intervention within WB ($P= 0.03; d= 1.83$) and HH cooling sessions ($P= 0.02; d= 1.75$) compared to CONT conditions (Figure 3.2C). Moreover, reduced HR values with WB ($d= 1.07$) and HH cooling ($d= 1.01$) over H cooling interventions were evident post-intervention. HR responses following WB cooling were significantly reduced ($P= 0.05; d= 1.07$) compared to CONT during the exercise protocol. Large ES indicated reduced HR values following WB cooling compared to H ($d= 1.25$) and HH cooling ($d= 1.34$) during the exercise protocol.
Pre-exercise USG was not significantly different between WB cooling (1.018 ± .006), HH cooling (1.017 ± 0.005), H (1.017 ± 0.008) or CONT conditions (1.017 ± 0.008; \( P = 0.70 - 0.84 \); d= 0.06 – 0.22). Body mass changes from non-urine fluid loss post-exercise were significantly less with WB cooling compared to CONT (1.8 ± 0.2 v 2.2 ± 0.4; \( P = 0.01 \); d= 1.58). Large ES data indicated less sweat losses from changes in body mass with WB cooling compared to HH (2.0 ± 0.4; d= 0.82) and H cooling (2.1 ± 0.5; d= 1.00) respectively.

**Neuromuscular**

No significant differences and trivial to moderate ES (Table 3.2; \( P = 0.07 - 0.87 \); d= 0.03 – 0.68) were observed between respective cooling conditions for mean MVC at all time points. Mean MVC was significantly reduced pre- to post-exercise in H cooling (\( P = 0.04 \); d= 1.09) and CONT conditions (\( P = 0.01 \); d= 1.46). Pre- to post-exercise differences in mean MVC were not significantly different, with trivial to small ES data following WB and HH cooling (\( P = 0.432 - 0.925 \); d= 0.04 – 0.35). No significant differences were evident between respective cooling volumes for post-intervention TPt (Table 3.2; \( P = 0.52 - 0.92 \)). However, large ES were evident for faster TPt mid-exercise with faster responses evident in the WB cooling compared to H (d= 1.13) and CONT sessions (d= 1.07). Changes in pre- to post-exercise Tpt were not significant, though moderate ES were detected for reduced Tpt in CONT (\( P = 0.39 \); d=0.79), H (\( P = 0.34 \); d=0.74) and HH (\( P = 0.47 \); d=0.65). Conversely, a large ES depicts slower Tpt pre- to post-exercise for WB (\( P = 0.11 \); d=1.16). No significant differences and trivial to moderate ES (Table 3.2; d= 0.03 – 0.45) were detected between VA at all time points. Finally, no significant change, though moderate to large ES were detected pre- to post-exercise for reduced VA (\( P = 0.06 - 0.47 \); d= 0.72 – 2.03).
Figure 3.2. A Mean ± SD core temperature, B skin temperature and C heart rate for Whole Body, Head + Hand, Head and Control conditions.

- A: Core temperature
- B: Skin temperature
- C: Heart rate

Significant differences:
- \(a\): Between Whole Body and Control conditions (P < 0.05).
- \(b\): Between Whole Body and Head conditions (P < 0.05).
- \(c\): Between Whole Body and Head + Hand conditions (P < 0.05).
- \(d\): Between Head + Hand and Control conditions (P < 0.05).
- \(e\): Between Head + Hand and Head conditions (P < 0.05).
- \(f\): Between Head and Control conditions (P < 0.05).

Large ES:
- \(1\): Between Whole Body and Control conditions (d > 0.8).
- \(2\): Between Whole Body and Head conditions (d > 0.8).
- \(3\): Between Whole Body and Head + Hand conditions (d > 0.8).
- \(4\): Between Head + Hand and Control conditions (d > 0.8).
- \(5\): Between Head + Hand and Head conditions (d > 0.8).
- \(6\): Between Head and Control conditions (d > 0.8).
Biochemical analyses

No significant differences ($P= 0.06 – 1.00$) were evident between conditions in pH, glucose, [La−] or HCO₃ markers pre- or post-exercise (Figure 3.3). Significant differences and large ES indicated reduced [La−] concentrations mid-exercise with WB cooling compared to CONT ($P= 0.02; d= 1.64$). Further, lower [La−] values were evident mid-exercise with WB compared to H cooling conditions ($d= 1.36$). Large ES indicated reduced glucose concentrations post-exercise between HH cooling with H cooling ($d= 0.82$) and CONT sessions ($d= 1.03$). No significant differences and trivial to moderate trends ($P= 0.25 – 1.00; d= 0.00 – 0.59$) were determined for all pre-exercise CK, CRP, TEST, INS and CORT concentrations (Table 3.3). Large ES indicated reduced post-exercise CK measures with WB ($d= 0.82$) and H cooling ($d= 0.83$) compared to CONT conditions. Large ES data were detected for CORT levels within the WB cooling condition and were increased compared to CONT ($d= 1.06$) post-exercise. No significant change and trivial to moderate ES were detected for all remaining post-exercise venous blood variables of CK, CRP, TEST, INS and CORT ($P= 0.07 – 0.99; d= 0.00 – 0.58$).

Perceptual measures

Significantly reduced mean RPE values were evident for WB ($4.2 ± 0.8; P= 0.03; d= 1.17$), HH ($4.6 ± 0.7; P= 0.04$) and H cooling conditions ($4.6 ± 0.8; P= 0.02$) compared to CONT condition ($4.9 ± 1.0$). Significant differences and large ES data indicate reduced mean TSS with WB cooling ($5.2 ± 0.5$) compared to HH ($5.7 ± 0.4; P= 0.00; d= 1.69$), H ($5.8 ± 0.5; P= 0.01; d= 1.95$) and CONT conditions ($6.3 ± 0.6; P= 0.00; d= 2.93$). Moreover, significantly reduced TSS values during HH ($P= 0.01; d= 1.87$) and H cooling ($P= 0.00; d= 1.28$) were evident compared to CONT sessions.
Table 3.2. Mean ± SD mean peak torque, time to peak torque and voluntary activation (VA) level for Whole Body, Head + Hand, Head and Control conditions pre-intervention, post-intervention, mid-exercise and post-exercise.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>Head</th>
<th>Head+Hand</th>
<th>Whole Body</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-Intervention</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Peak Torque (Nm)</td>
<td>167.3 ± 37.0</td>
<td>163.1 ± 42.3</td>
<td>157.8 ± 39.2</td>
<td>162.3 ± 37.4</td>
</tr>
<tr>
<td>Time to Peak Torque (ms)</td>
<td>98.0 ± 11.1</td>
<td>96.6 ± 16.8</td>
<td>92.4 ± 16.8</td>
<td>88.1 ± 11.0</td>
</tr>
<tr>
<td>VA Level (%)</td>
<td>75.6 ± 8.9</td>
<td>74.7 ± 6.9</td>
<td>73.3 ± 9.5</td>
<td>78.4 ± 9.1</td>
</tr>
<tr>
<td><strong>Post-Intervention</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Peak Torque (Nm)</td>
<td>159.9 ± 47.7</td>
<td>162.7 ± 36.1</td>
<td>153.3 ± 27.4</td>
<td>144.2 ± 36.4</td>
</tr>
<tr>
<td>Time to Peak Torque (ms)</td>
<td>94.6 ± 12.0</td>
<td>97.1 ± 16.5</td>
<td>99.9 ± 18.1</td>
<td>96.7 ± 13.1</td>
</tr>
<tr>
<td>VA Level (%)</td>
<td>70.7 ± 17.1</td>
<td>75.8 ± 18.1</td>
<td>72.2 ± 11.6</td>
<td>68.4 ± 9.1</td>
</tr>
<tr>
<td><strong>Mid-Exercise</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Peak Torque (Nm)</td>
<td>142.9 ± 50.2</td>
<td>146.4 ± 26.2</td>
<td>145.1 ± 25.0</td>
<td>158.0 ± 21.9</td>
</tr>
<tr>
<td>Time to Peak Torque (ms)</td>
<td>93.3 ± 15.0</td>
<td>92.8 ± 12.1</td>
<td>90.1 ± 15.5</td>
<td>81.4 ± 16.3&lt;sup&gt;12&lt;/sup&gt;</td>
</tr>
<tr>
<td>VA Level (%)</td>
<td>65.0 ± 9.8</td>
<td>66.3 ± 14.1</td>
<td>68.7 ± 15.4</td>
<td>69.6 ± 18.2</td>
</tr>
<tr>
<td><strong>Post-Exercise</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Peak Torque (Nm)</td>
<td>139.3 ± 54.0&lt;sup&gt;†&lt;/sup&gt;</td>
<td>139.7 ± 29.5&lt;sup&gt;†&lt;/sup&gt;</td>
<td>150.8 ± 46.1</td>
<td>151.1 ± 28.9</td>
</tr>
<tr>
<td>Time to Peak Torque (ms)</td>
<td>93.1 ± 14.0</td>
<td>90.1 ± 9.7</td>
<td>86.7 ± 12.5</td>
<td>95.2 ± 15.9</td>
</tr>
<tr>
<td>VA Level (%)</td>
<td>68.9 ± 15.9&lt;sup&gt;†&lt;/sup&gt;</td>
<td>68.6 ± 9.4&lt;sup&gt;†&lt;/sup&gt;</td>
<td>69.5 ± 12.2</td>
<td>67.5 ± 16.8&lt;sup&gt;†&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Significant difference compared to Control condition ($P < 0.05$). <sup>b</sup> Significant difference compared to Head condition ($P < 0.05$). <sup>c</sup> Significant difference compared to Head + Hand condition ($P < 0.05$). <sup>1</sup> Large ES compared to Control condition ($d > 0.80$). <sup>2</sup> Large ES compared to Head condition ($d > 0.80$). <sup>3</sup> Large ES compared to Head + Hand condition ($d > 0.80$). <sup>4</sup> Significant difference compared to pre-intervention values ($P < 0.05$). <sup>†</sup> Large ES compared to pre-intervention values ($d > 0.80$).
Table 3.3. Mean ± SD biochemical comparison between Whole Body, Head + Hand, Head and Control conditions and over time.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>Head</th>
<th>Head+Hand</th>
<th>Whole Body</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK (U L⁻¹)</td>
<td>Pre</td>
<td>301 ± 193</td>
<td>231 ± 137</td>
<td>248 ± 169</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>645 ± 594</td>
<td>392 ± 133ᵃ</td>
<td>411 ± 187</td>
</tr>
<tr>
<td>CRP (mg L⁻¹)</td>
<td>Pre</td>
<td>2.8 ± 4.4</td>
<td>2.8 ± 4.3</td>
<td>2.7 ± 4.1</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>2.9 ± 4.5</td>
<td>3.0 ± 4.5</td>
<td>2.8 ± 4.3</td>
</tr>
<tr>
<td>INS (µL mL⁻¹)</td>
<td>Pre</td>
<td>5.6 ± 1.7</td>
<td>6.5 ± 2.9</td>
<td>5.9 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>5.9 ± 2.4</td>
<td>5.7 ± 1.4</td>
<td>5.9 ± 0.6</td>
</tr>
<tr>
<td>TEST (ng dL⁻¹)</td>
<td>Pre</td>
<td>401 ± 85</td>
<td>368 ± 50</td>
<td>385 ± 103</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>524 ± 126</td>
<td>505 ± 99</td>
<td>471 ± 131</td>
</tr>
<tr>
<td>CORT (nmol L⁻¹)</td>
<td>Pre</td>
<td>319 ± 115</td>
<td>299 ± 118</td>
<td>299 ± 140</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>544 ± 211</td>
<td>611 ± 161</td>
<td>602 ± 161</td>
</tr>
</tbody>
</table>

ᵃ Large ES compared to control (d > 0.80).
Chapter 3 – Pre-cooling Volume

Figure 3.3. Mean ± SD capillary blood comparison of anaerobic metabolites between Whole Body, Head + Hand, Head and Control conditions and over time.

\[ \text{A} \]
\[ \text{pH (AU)} \]

\[ \text{B} \]
\[ \text{Glucose (mmol} \cdot \text{L}^{-1}) \]

\[ \text{C} \]
\[ \text{Lactate (mmol} \cdot \text{L}^{-1}) \]

\[ \text{D} \]
\[ \text{HC03 (mmol} \cdot \text{L}^{-1}) \]

\(^{a}\) Significant difference between Whole Body and Control conditions \((P < 0.05)\). \(^{1}\) Large ES between Whole Body and Control conditions \((d > 0.80)\). \(^{2}\) Large ES between Whole Body and Head conditions \((d > 0.80)\). \(^{3}\) Large ES between Head + Hand and control conditions \((d > 0.80)\). \(^{4}\) Large ES between Head + Hand and Head conditions \((d > 0.80)\). \(^{5}\) Large ES between Head and Control conditions \((d > 0.80)\).
Discussion

The aim of this investigation was to determine the effects of volume-dependent pre-cooling on physiological and performance outcomes for self-paced intermittent-sprint exercise in the heat. In addition we attempted to determine the related volume effect on neuromuscular function as related to intermittent-sprint exercise performance in the heat. The novel finding of this study is that performance appears to be affected by the dose of pre-cooling, in that larger surface area coverage resulted in increased work capacity, with greater suppression of physiological load. Most salient, was that pre-cooling resulted in the maintenance of MVC even though there was increased work completed across the respective cooling interventions. These findings indicate that enhanced thermoregulatory control following pre-cooling may negate the down-regulation of exercise performance in the heat, and hence allows for the maintenance of skeletal muscle recruitment and work output.

Exercise and environmentally induced heat stress may severely impair exercise capacity through reduced time to fatigue and an inability to maintain desired intensities (González-Alonso et al., 1999; Nybo & Nielsen, 2001a). Results from the current investigation are consistent with previous pre-cooling studies of attenuated thermoregulatory strain and improved intermittent-sprint exercise performance in the heat (Castle et al., 2006; Duffield & Marino, 2007; Duffield et al., 2009d). A common feature of the present study and previous work (Duffield & Marino, 2007) is the pre-cooling induced improvements in self-paced, sub-maximal distances covered between maximal sprint exercise bouts. The step-wise response to cooling resulted in the reduction in distance covered as the volume of cooling was reduced. However, through the use of WB cooling, participants covered greater hard running and jogging distances in Spells 1 and 2 respectively (Table 3.1, Figure 3.1B). Similarly, larger
cooling application was associated with greater maintenance of maximal sprint times (Table 3.1, Figure 3.1A). Hence, the current study corroborates previous research which shows performance benefits for free-paced intermittent-sprint exercise in the heat (Castle et al., 2006; Duffield & Marino, 2007; Duffield et al., 2009d).

Unique to the current intermittent-sprint pre-cooling study was the collection of neuromuscular data at set time points during the testing session, rather than purely pre- and post-exercise. The attenuated thermoregulatory loads observed with WB cooling maintained MVC mid- and post-exercise (Table 3.2). These changes are apparent despite the absence of condition-specific differences in % VA (Table 3.2). Exercise and environmentally induced hyperthermia seemingly reduce skeletal muscle force output through the impairment of VA (Nybo & Nielsen, 2001a; Morrison et al., 2004; Todd et al., 2005; Thomas et al., 2006). However, an inverse relationship between muscle function and Tc is apparent as isometric MVC and % VA returns to baseline following the resumption of normative Tc values (Morrison et al., 2004; Thomas et al., 2006). Hence it is postulated that neuromuscular responses to exercise in the heat are directly linked to elevated thermal load in addition to any protocol-specific fatigue (Morrison et al., 2004; Thomas et al., 2006). Accordingly, the blunting of Tc during exercise and subsequent preservation of MVC and VA with more extensive cooling (Figure 3.2A) may account for the relationship between cooling volumes and self-paced running workloads. That said, an inability to directly assess muscle function during the exercise protocol mean factors relating to physiological strain or anticipatory regulation of CNS responses cannot be overlooked (Marino, 2004; Duffield et al., 2010).
Given the lack of difference in VA between cooling volumes, the increased distances covered during self-paced exercise bouts may not be completely accounted for solely by peripheral or central factors. Rather, it is plausible that an interaction of afferent and efferent stimuli, combined with a reduced perceptual strain following pre-cooling may augment muscle recruitment during exercise, which manifests as a sustained MVC mid- and post-exercise, despite the increased workloads performed (Tucker, 2009; Duffield et al., 2010). Although electromyographic responses were not measured in the present study, a faster Tpt mid-exercise was evident with WB cooling. The faster Tpt may highlight the protective properties of pre-cooling for exercise in the heat (Duffield, 2008). Accordingly, pre-cooling may improve the adopted pacing strategy during self-selected work in the heat (Kay et al., 1999; Duffield et al., 2010), essentially due to a greater preservation of MVC via maintenance of muscle recruitment (Kay et al., 2001) and subsequent curbing in the down-regulation of exercise intensity in the heat (as noted in the control condition).

While WB cooling is often reported as the gold-standard of cooling interventions, part-body cooling techniques may also have favorable physiological and performance benefits (Arngrímsson et al., 2004; Castle et al., 2006). Results from the present study demonstrate cooling volume to seemingly influence both the physiological response and ensuing intermittent-sprint exercise performance. Maintenance of repeated sprint time was evident in all pre-cooling conditions in Spell 1, though this trend was only continued in the WB condition during Spell 2 following the re-application of cooling procedures (Table 3.1; Figure 3.1A). Further, increased hard running and jogging distances covered during self-paced exercise bouts imply the presence of improved maintenance of exercise intensities (Kay et al., 1999; Duffield et al., 2010) following WB in contrast to part-body or no cooling conditions (Table 3.1; Figure 3.1B). Further, as with the maintenance of MVC, a step-wise interaction
seemed evident, in that; the use of HH cooling indicated some performance benefits over the
CONT condition. Conversely, reduced surface area coverage with H cooling and CONT
provided little or no performance improvement, resulting in either the slowest sprint
performances, or least distance covered. These findings support the existence of a dose-
dependent response to cooling application and performance outcomes (Castle et al., 2006).

The attenuation of thermal load, through the application of pre-cooling, and subsequent
improvements in heat storage and dissipation capacities, increases the period for optimal
exercise performance prior to the attainment of critical $T_c$ in lab settings (González-Alonso et
al., 1999). Accordingly, WB cooling was most effective in reducing $T_c$ and $T_{sk}$ pre-exercise
and continuing to blunt the rise in body temperature for the duration of the exercise protocol.
Increased cooling volumes may result in greater physiological perturbations, or the prolonged
suppression of increased physiological loads (Daanen et al., 2006; Duffield & Marino, 2007);
hence the volume effect of cooling observed in the present investigation is not surprising.
Nevertheless, an attenuated thermoregulatory response during exercise in the heat may delay
redistribution of cardiac output to the periphery and sweat responses for heat dissipation
(Casa, 1999). Moreover, the maintenance of central blood volume protects against reduced
stroke volume and associated cardiovascular strain (González-Alonso et al., 2008). Pre-
cooling induced reductions in cardiovascular strain are observed during set-paced exercise
protocols (Lee & Haymes, 1995; Arngrímsson et al., 2004), yet higher workloads during self-
paced exercise appear to conceal this effect (Kay et al., 1999; Duffield & Marino, 2007;
Duffield et al., 2009d).
In contrast, marked reductions in HR were observed following WB cooling, in spite of higher workloads completed. Given the 20 – 30 min time frame during which the effects of pre-cooling remain evident (Wilson et al., 2002), the length of spells and cooling reapplication mid-session might overstate the volume effects in this case. However, limited cardiovascular drift may reflect improved blood volume status owing to decreased sweating demands (Mountain & Coyle, 1992). Restricted fluid intake and sweat loss alterations in nude body mass in the present study between 2.4 – 2.9% exceed levels contributing to heightened thermal strain and aerobic performance decrements (Casa et al., 2005). Nevertheless, differences in sweat rate (~400 mL) between WB cooling and CONT conditions may not adequately explain HR variance, nor augmented shuttle-running performance (González-Alonso et al., 2008). Thus, it is likely multiple afferent and efferent indicators owing to reduced physiological (sweat loss, $T_c$ and HR) and perceptual loads (RPE and TSS) promote continued maintenance of exercise intensity, muscle recruitment and voluntary force production (Tucker, 2009; Duffield et al., 2010).

In accordance with previous reports, analysis of blood markers of anaerobic metabolites and muscle damage demonstrated minimal differences between conditions (Drust et al., 2000; Liang et al., 2001; Castle et al., 2006; Duffield & Marino, 2007). Given the well documented alterations in metabolism associated with exercise in the heat (Febbraio, 2001) and the reduced physiological responses to exercise with pre-cooling and/or augmented performance outcomes (Marino, 2002; Quod et al., 2008; Duffield et al., 2010), the lack of differences in metabolic markers is not unexpected. Yet reduced [La'] mid- and post-exercise with greater cooling volumes are inconsistent with elevated self-paced running distances and maintenance of maximal sprints speeds. Similarly, reduced CK concentrations post-exercise in WB and HH cooling despite higher workloads may be a result of reduced levels of heat stress.
experienced during these conditions (Alzeer et al., 1997). Nevertheless, WB cooling appears to have stimulated sympatho-adrenal activity and subsequently increased CORT secretion as detected post-exercise. Whilst reduced sweat rates with more extensive pre-cooling may have assisted in explaining reduced [La\(^{-}\)] and CK concentrations, elevated CORT may be attributed to higher workloads completed or the larger cooling stimulus. As such, despite the reduced physiological strain evident during the (larger volume) cooling conditions, the increased work performed seems to still invoke greater generic stress responses.

In conclusion, this investigation highlights the dose-response relationship evident between pre-cooling volume and ensuing physiological, perceptual and performance outcomes in hot conditions (Castle et al., 2006; Daanen et al., 2006; Duffield & Marino, 2007). Improved performance responses may result from the maintenance of exercise intensities during self-paced exercise bouts, and potentially relate to the maintenance of skeletal contractile function (MVC). Moreover, despite WB methods proving most effective, part-body techniques also offer a blunted thermoregulatory response, albeit to a lesser extent. These responses may owe to pre-cooling induced suppression of thermoregulatory responses to exercise in the heat allowing for enhanced physiological control and reduced perceptual efforts. Reduced levels of heat stress with pre-cooling may facilitate the maintenance of MVC through the maintenance of muscle recruitment, thereby permitting higher work output. From a practical perspective, field-based practitioners should be aware of the inverse relationship between volume of cooling and performance benefits. In addition, practitioners should select interventions that allow for sufficient volume, yet within logistical constraints of their individual team contexts.
CHAPTER 4

Duration-Dependant Response of Mixed-Method Pre-Cooling for Intermittent-Sprint Exercise in the Heat

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Abstract

This study examined the effects of pre-cooling duration on performance and neuromuscular function for self-paced intermittent-sprint shuttle running in the heat. Eight male, team-sport athletes completed two 35-min bouts of intermittent-sprint shuttle running separated by a 15-min recovery on three separate occasions (33°C, 34% relative humidity). Mixed-method pre-cooling was completed for 20-min (COOL20), 10-min (COOL10) or no cooling (CONT) and reapplied for 5-min mid-exercise. Performance was assessed via sprint times, % decline and shuttle-running distance covered. Maximal voluntary contractions (MVC), voluntary activation (VA) and evoked twitch properties were recorded pre- and post-intervention and mid- and post-exercise. Core temperature ($T_c$), skin temperature, heart rate, capillary blood metabolites, sweat losses, perceptual exertion and thermal stress were monitored throughout. Venous blood draws pre- and post-exercise were analysed for muscle damage and inflammation markers. Shuttle-running distances covered were increased 5.2±3.3% following COOL20 ($P < 0.05$), with no differences observed between COOL10 and CONT ($P > 0.05$). COOL20 aided in the maintenance of mid- and post-exercise MVC ($P < 0.05$; $d > 0.80$), despite no conditional differences in VA ($P > 0.05$). Pre-exercise $T_c$ was reduced by 0.15 ± 0.13°C with COOL20 ($P < 0.05$; $d > 1.10$), and remained lower throughout both COOL20 and COOL10 compared to CONT ($P < 0.05$; $d > 0.80$). Pre-cooling reduced sweat losses by 0.4 ± 0.3 kg ($P < 0.02$; $d > 1.15$), with COOL20 0.2 ± 0.4 kg less than COOL10 ($P= 0.19$; $d= 1.01$). Increased pre-cooling duration lowered physiological demands during exercise heat stress and facilitated the maintenance of self-paced intermittent-sprint performance in the heat. Importantly, the dose-response interaction of pre-cooling and sustained neuromuscular responses may explain the improved exercise performance in hot conditions.
Introduction

High ambient temperatures impair heat loss mechanisms, requiring an alteration in physiological and behavioural processes to balance rising internal body temperatures with the maintenance of exercise performance (Wendt et al., 2007). Pre-cooling induced improvements to heat storage may reduce these challenges, resulting in augmented work rates and extended exercise time (Marino, 2002; Quod et al., 2006; Duffield, 2008). Evidence from pre-cooling studies demonstrate performance benefits to be associated with suppressed skin and/or core temperature, cardiovascular, metabolic and perceptual loads (Lee & Haymes 1995; Arngrímsson et al., 2004; Hasegawa et al., 2005; Castle et al., 2006; Duffield & Marino 2007). However, evidence against critical limiting temperatures (Ely et al., 2009), and study of self-paced exercise modes (Kay et al., 1999; Duffield et al., 2010), may suggest the integration of higher central regulation to control skeletal muscle recruitment in anticipation or response to increased thermal loads (Nybo & Nielsen 2001a; Marino, 2004; Tucker et al. 2004).

Heat stress ultimately disrupts central motor output, down-regulating skeletal muscle recruitment, voluntary activation and force output (Kay et al., 2001; Nybo & Nielsen 2001a; Morrison et al., 2004; Todd et al., 2005). In spite of potential afferent or efferent origins (Marino, 2004), thermal advantages obtainable with pre-cooling may safeguard neuromuscular pathways, protecting exercise performance in the heat and assisting to explain the maintenance of higher exercise intensities (Kay et al., 1999; Duffield et al., 2010). Previous research provides evidence for a dose-response relationship with pre-cooling (Castle et al., 2006; Daanen et al., 2006; Duffield & Marino, 2007; Minett et al., 2011), whereby the greater the cooling stimulus to improve thermoregulatory efficiency, the lower the rate of
Chapter 4 – Pre-cooling Duration

heat storage and the better the ensuing performance outcome (González-Alonso et al., 1999). This ergogenic assistance has traditionally been linked with observed reductions in core temperature (Marino, 2002), although cooler skin temperatures independent of core temperature change also appear to have some regulation of exercise intensity (Kay et al., 1999; Schlader et al., 2011). These findings have practical implications for most athletic disciplines, but might be of particular importance for team-sport athletes who experience higher internal body temperatures during intermittent activity compared with steady state exercise modes (Ekblom et al., 1971).

The benefits of whole-body cold-water immersion are widely acknowledged and potentially relate to the volume of cold exposure provided by such a method (Marino, 2002; Quod et al., 2006; Duffield, 2008). However, issues of practicality surrounding its application in competitive situations provide difficulties to implementation and pre-event routines (Marino, 2002; Quod et al., 2006). Whilst logistical concerns in the field may be eased through the manipulation and combination of multiple cooling techniques (Duffield & Marino, 2007; Quod et al., 2008; Duffield et al., 2009d; Minett et al., 2011; Ross et al., 2011), the influence of pre-cooling duration on ensuing physiological and performance responses is unknown. These data may prove important to the effective implementation of pre-cooling techniques, particularly given the potential for extended physiological benefits and subsequent performance gains with more extensive cooling exposure (Minett et al., 2011). Alternatively, any excessive dose of cooling duration resulting in pronounced reduction in skeletal muscle temperature (Peiffer et al., 2009b) may be detrimental to motor unit recruitment and force output (Racinais & Oksa, 2010). Accordingly, understanding the balance between reduced thermal loads and retaining muscle function is of value in optimising performance outcomes following pre-cooling.
Evidence supports the use of pre-cooling for intermittent-sprint exercise performance in the heat (Castle et al., 2006; Duffield & Marino, 2007; Duffield et al., 2009d; Minett et al., 2011). Pre-cooling induced enhancements in heat storage capacity may reduce thermoregulatory strain, facilitating the maintenance of neuromuscular function and subsequent exercise performance (Duffield et al., 2010). Nevertheless, understanding pre-cooling duration required for ergogenic effects is lacking. Further, the relationship between pre-cooling duration, voluntary force and evoked twitch properties and self-paced exercise performance in the heat warrants further investigation. Hence, the aim of the present study is to investigate the effects of pre-cooling duration on self-paced intermittent-sprint exercise performance, physiological responses and neuromuscular function in hot environmental conditions.

Methods

Participants

Eight, moderate- to well-trained, male team-sport athletes were recruited for this study (mean ± SD: age 21.5 ± 2.7 yr; height 184.1 ± 9.7 cm; body mass 78.9 ± 8.2 kg). Participants were club and regional level athletes (cricket and field hockey) who reported completing 3-5 sports specific and conditioning training sessions per week and competition on a weekly basis. All participants gave verbal and written consent before engaging in testing procedures and ethical clearance was given by the Ethics in Human Research Committee of the University.
Experimental Design

Participants reported to the laboratory for testing sessions on four separate occasions. Following an initial equipment and procedural familiarisation session that included completion of the exercise protocol in its entirety, the remaining three visits were conducted in a randomised, repeated measures cross-over fashion. The data reported in this paper were collected as part of a succession of cricket related investigations focused on fast bowling related intermittent-sprint exercise in the heat. In accordance with previous reports (Minett et al., 2011), fast bowling workload data (Petersen et al., 2010b) were utilised to provide for a non-specific team-sport protocol to reflect previous research (Duffield & Marino 2007). All respective testing sessions were conducted on an enclosed 20 m synthetic running track in mean ± SD environmental conditions of 33.0 ± 0.9°C and 33.9 ± 5.9% relative humidity. Temperatures were controlled using a customised gas heating system and four electronic 2,000 W room heaters (Kambrook, Port Melbourne, Australia) positioned at 5 m increments alongside the running track. All testing sessions were identical, with only pre-cooling duration variable throughout. Participants performed three conditional trials, including a control session (no pre-cooling), 10 min pre-cooling session and a 20 min pre-cooling session. All participants were required to refrain from strenuous exercise and alcohol 24 h before and all caffeine and food substances 3 h before each testing session.

Exercise protocol

During all sessions, participants performed a standardised 5 min warm-up followed by 2 x 35 min bouts (Bout 1 and 2) of intermittent-sprint activity, separated by a 15 min mid-exercise recovery interval. Warm-up procedures involved progressively increasing continuous 20 m shuttle run speeds and six repeated 15 m maximal sprints. Each identical bout consisted of a
set pattern of intermittent-sprint, hard running, jogging and walking activities to reflect cricket fast bowling requirements (Petersen et al., 2010b). Specifically, the exercise protocol involved 10 (2 x 5) sets of 6 x 15 m maximal sprints with a 30 s recovery to emulate a 6-ball cricket over. Further, 5 min periods between sprint sets were comprised of minute by minute periods of self-paced, sub-maximal exercise intensities as per Duffield and Marino (2007). Hard running, jogging and walking activity was performed in a 15 m shuttle run fashion, with participants resuming their starting position at 50 s of each self-paced minute to begin the following exercise intensity. Participants were offered verbal support throughout and instructed to cover the greatest distance possible during hard run efforts, while jogging and walking were completed at self-paced intensities. To limit potentially confounding effects of any fluid intake, all consumption was restricted throughout each session. The reliability of mean sprint times, self-paced distances and hard running distances covered demonstrate the Pearson Product-Moment Correlation (r) as 0.94 – 0.98, Technical Error of Measurement as 0.02 – 1.5% and Co-efficient of Variation (CV) as 0.6 – 1.1% (Minett et al., 2011). A schematic representation of the exercise protocol is presented in Figure 4.1.
**Figure 4.1.** Schematic representation of the self-paced intermittent-sprint exercise protocol. MVC represents maximal voluntary contraction. VB represents venous blood sample. CB represents capillary blood sample. HR represents heart rate. $T_c$ represents core temperature. $T_{sk}$ represents skin temperature. RPE represents rating of perceived exertion. TSS represents thermal sensation scale.
**Pre-cooling intervention**

Cooling apparatus were applied pre-exercise and for the final 5 min of the 15 min mid-exercise recovery interval in the two treatment trials. Durational effects of pre-cooling were determined by the comparison of control (CONT), 10 min (COOL10) and 20 min (COOL20) pre-cooling interventions. As per Minett et al. (2011) all pre-cooling procedures involved a mixed-method approach, whereby participants were cooled with an iced towel soaked in water (5.0 ± 0.5°C) covering the head, neck and shoulders, hands immersed to the wrist in cold water (9.0 ± 0.5°C), ice-vest covering the torso (Arctic Heat, Brisbane, Australia) and frozen ice-packs applied to the quadriceps (Techni Ice, Frankston, Australia). Ice-vests and ice-packs were stored at -20°C before and after application. No cooling stimuli were applied during the 20 min CONT trial. All treatments were completed as participants rested passively in a seated position in controlled laboratory conditions of 33°C and 34% relative humidity. Mixed-method pre-cooling presents a practical and ecologically valid alternative to cold water immersion (Duffield et al., 2009d), with the larger surface area coverage, the greater the ergogenic effect (Minett et al., 2011).

**Measures**

**Performance**

Intermittent-sprint running performance was assessed via 15 m sprint time measured with an infra-red timing system (Speed-Light, Swift, Wacol, Australia). Self-paced distances accumulated were calculated using 1 m markings along the 15 m running track. Percentage decline in sprint times [(total time/(fastest time · sprint n) · 100)] are reported as an indicator
of performance maintenance. Self-paced, sub-maximal exercise bouts are reported as an individual mean or total value for each exercise mode (walk, jog, hard run).

**Neuromuscular function**

Evaluation of maximal voluntary contractions (MVC) and evoked twitch properties of the right knee extensors were recorded pre-intervention, post-intervention, mid-exercise and post-exercise with an isokinetic dynamometer (Kin-Com, Model 125, Chattanooga Group Inc., Hixon, USA) and customised computer software (v8.0, LabVIEW; National Instruments, North Ryde, Australia). The axis of rotation of the dynamometer was visually aligned with the lateral femoral epicondyle. Participants were fastened to the dynamometer chair with knee and hip positioned at 90° (0° represents full extension) using conventional shoulder and waist straps and the distal right leg fixed to the lever arm 1 cm above lateral malleolus. Supra-maximal activation of the femoral nerve was achieved via a single square-wave pulse with a width of 200 µs (400 V with a current of 100-450 mA) delivered by a Digitimer DS7 stimulator (Digitimer Ltd., Welwyn Garden City, England) linked to a BNC2100 terminal block and signal acquisition system (PXI1024; National Instruments, Austin, USA). Muscle activation was achieved with reusable self-adhesive gel electrode cathode positioned on the anterior thigh 3 cm below the inguinal fold (diameter 10 mm; MEDI-TRACE™ Mini 100 Pediatric Foam Electrodes, Covidien, Mansfield, USA). A 90 x 50 mm reusable self-adhesive gel electrode anode was located on the medio-posterior aspect of the upper thigh below the gluteal fold (Verity Medical Ltd., Stockbridge, England). Peak twitch force was identified through incremental increases in stimulus intensity and then increased by 10% to ensure supra-maximal stimulation. Baseline evoked twitch properties were determined through five pulses separated by 20 s delivered in a rested state. Assessment
of muscle function involved a MVC protocol involving 5 x 5 s isometric trials with a superimposed twitch following attainment of MVC plateau to the resting muscle immediately post-contraction. Individual MVC efforts were separated by a 30 s recovery period. MVC was defined as the peak torque (Pt) value attained during voluntary contractions. Voluntary activation (VA) was calculated according to the twitch interpolation technique (Allen et al., 1995). Time to peak torque (TPt) was defined as the time from evoke force onset to peak potentiated twitch torque. Data was processed using MATLAB version 7.9.0.529 (R2009b, The Mathworks Inc., Natick, USA).

*Physiological variables*

A mid-stream urine sample was collected on arrival to the laboratory to determine urine specific gravity (USG; Refractometer 503, Now. Nippon Optical, Works Co, Tokyo, Japan). Changes in nude body mass were recorded pre- and post-exercise using calibrated scales (HW 150 K, A & D, Thebarton, Australia) to estimate total body sweat loss. Heart rate (HR) was determined with a chest transmitter and wristwatch receiver (FS1; Polar Electro Oy, Kempele, Finland). Core temperature (Tc) was measured using a telemetric temperature capsule (VitalSense, Mini Mitter, Bend, USA) ingested 5 h pre-exercise to allow for passing into the gastrointestinal tract. HR and Tc was recorded every 5 min during the intervention and mid-exercise rest period, and at 10 min intervals during the exercise protocol. Skin temperature (Tsk) was measured at four sites (sternum, mid-forearm, mid-quadriceps and medial calf) with an infra-red thermometer (ThermoScan 3000, Braun, Kronberg, Germany) as per Burnham et al. (2006) (ICC= 0.96; r= 0.92). Tsk was recorded at 5 min increments during the pre-cooling intervention, mid-protocol break and post-exercise. Mean Tsk was
calculated using the Ramanathan (1964) formula and body heat storage was estimated according to the equation of Havenith et al. (1995).

**Blood collection and biochemical analysis**

Resting blood draws were collected to determine the effect of pre-cooling duration on anaerobic metabolites, muscle damage, inflammation and stress responses. Capillary blood samples were drawn from a hyperaemic earlobe to analyse pH, glucose, lactate [La\(^-\)] and bicarbonate (HCO\(_3\)) (ABL825 Radiometer, Copenhagen, Denmark). Further capillary blood draws mid- and post-exercise were collected within 30 s of exercise completion. Venous blood samples were drawn from an antecubital vein with an evacuated venipuncture assembly and serum separator tubes (Monovette, Sarstedt, Numbrecht, Germany). Serum was obtained through centrifugation (4000 rpm for 10 min) and stored at -20ºC until analysis. Serum concentrations of creatine kinase (CK), C-reactive protein (CRP), testosterone (TEST), cortisol (CORT) and insulin (INS) were determined pre- and 30 min post-exercise. All serum samples were analysed according to manufacturer’s instructions provided in the respective assay kits. Analysis of CK was completed using enzymatic and bichromatic rate procedures and for CRP with the particle enhanced turbidimetric immunoassay technique (Dimension Xpand spectrophotometer, Dade Bearing, Atlanta, USA). INS, TEST and CORT were calculated using a solid-phase, competitive chemiluminescent enzyme immunoassay (Immulite 2000, Diagnostic Products Corp., Los Angeles, USA). Statistical analyses were performed on measured circulating concentrations as corrections for plasma and blood volume changes were not performed. All samples for each subject were analysed in the same assay run and intra-assay CV were < 5% for all venous blood analyses.
Perceptual measures

Rating of perceived exertion (RPE) and thermal sensation scale (TSS) were recorded every 5 min during pre-cooling and exercise protocols. RPE was determined according to the Borg CR-10 scale, where rankings ranged from 0 (nothing at all) to 10 (maximal). TSS was assessed using an 8-point Likert scale, ranging from 0 (unbearably cold) to 8 (unbearably hot).

Statistical analysis

Data are reported as mean ± standard deviation (SD). A two-way (condition x time) repeated-measures ANOVA was performed to detect differences between cooling durations (0 min vs. 10 min vs. 20 min). Unprotected pairwise comparisons (Protected Fisher’s LSD) were applied to determine the source of significance, which was accepted when P < 0.05. Analysis was performed using the Statistical Package for Social Sciences (SPSS v 16.0, Chicago, USA). Standardised effect sizes (ES; Cohen’s d) analyses were used in interpreting the magnitude of differences between conditions. An ES was classified as trivial (<0.20), small (0.20-0.49), moderate (0.50-0.79) or large (>0.80) as expressed by dividing the mean difference by the between-subject SD.
Results

**Self-paced intermittent-sprint exercise performance**

No significant differences and trivial to moderate ES ($P= 0.45 – 1.00; d= 0.00 – 0.40$) were present between all conditions for mean peak sprint times and % decline during Bout 1 (Table 1). However, significantly faster mean peak sprint times were observed in Bout 2 for COOL20 compared with CONT ($P= 0.02$; Figure 4.2A). Significant differences and large ES data indicated a smaller % decline during Bout 2 for COOL20 compared with CONT ($P= 0.04; d= 0.91$). No significant differences and trivial to moderate ES were apparent between cooling durations (10 v 20 min) for all sprint time variables ($P= 0.09 – 0.97; d= 0.01 – 0.38$).

Overall mean total distances covered were significantly greater following COOL20 (4801 ± 375 m) compared with COOL10 cooling (4584 ± 373 m; $P= 0.03; d= 0.82$) and CONT (4584 ± 411 m; $P= 0.01$). No significant difference and a trivial ES was observed for overall mean total distance accumulated between COOL10 cooling and CONT ($P= 0.90; d= 0.01$). Mean and total hard running distances completed in Bout 1 were significantly greater in COOL20 than in COOL10 ($P= 0.02; d= 1.14$) and CONT ($P= 0.03$) (Table 4.1; Figure 4.2B). Mean and total hard running distances were significantly increased for COOL20 compared with CONT in Bout 2 ($P= 0.01$). Mean and total jogging distances accumulated following COOL20 were also significantly greater than COOL10 in Bout 1 ($P= 0.04; d=1.15$) and Bout 2 ($P= 0.01$) respectively. No significant differences and trivial to moderate ES between conditions were observed for all mean and total distances covered for any walking measures ($P= 0.22 – 0.89; d= 0.04 – 0.48$).
Figure 4.2. A Mean ± SD individual 15-m sprint times (s) across all 20 min pre-cooling, 10 min pre-cooling and Control conditions. B Mean ± SD individual hard running distances (m) covered across all 20 min pre-cooling, 10 min pre-cooling and Control conditions.
Table 4.1. Mean ± SD sprint time variables and sub-maximal running distances covered per session for 20min pre-cooling, 10 min pre-cooling and Control conditions.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Control</th>
<th>10 min</th>
<th>20 min</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sprint time variables</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Bout 1 sprint (s)</td>
<td>2.59 ± 0.07</td>
<td>2.60 ± 0.15</td>
<td>2.61 ± 0.12</td>
</tr>
<tr>
<td>Mean Bout 2 sprint (s)</td>
<td>2.71 ± 0.13</td>
<td>2.68 ± 0.16</td>
<td>2.66 ± 0.11 a</td>
</tr>
<tr>
<td>Bout 1 decline (%)</td>
<td>5.62 ± 1.95</td>
<td>4.92 ± 1.88</td>
<td>6.50 ± 3.69</td>
</tr>
<tr>
<td>Bout 2 decline (%)</td>
<td>8.82 ± 4.83</td>
<td>6.95 ± 5.00</td>
<td>6.09 ± 3.55 a1</td>
</tr>
<tr>
<td><strong>Sub-maximal running distances</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Bout 1 hard run (m)</td>
<td>156.6 ± 17.2</td>
<td>153.0 ± 15.4</td>
<td>165.2 ± 15.4 ab2</td>
</tr>
<tr>
<td>Mean Bout 2 hard run (m)</td>
<td>146.6 ± 18.3</td>
<td>151.3 ± 14.9</td>
<td>154.3 ± 17.4 a</td>
</tr>
<tr>
<td>Mean Bout 1 jog (m)</td>
<td>107.2 ± 13.6</td>
<td>103.6 ± 7.5</td>
<td>110.4 ± 8.9 b2</td>
</tr>
<tr>
<td>Mean Bout 2 jog (m)</td>
<td>101.4 ± 12.0</td>
<td>101.2 ± 9.6</td>
<td>105.8 ± 9.5 b</td>
</tr>
<tr>
<td>Mean Bout 1 walk (m)</td>
<td>63.6 ± 4.5</td>
<td>62.9 ± 4.4</td>
<td>64.6 ± 5.4</td>
</tr>
<tr>
<td>Mean Bout 2 walk (m)</td>
<td>60.7 ± 6.1</td>
<td>61.7 ± 5.6</td>
<td>61.5 ± 5.9</td>
</tr>
<tr>
<td>Total Bout 1 hard run (m)</td>
<td>1252.9 ± 137.8</td>
<td>1223.8 ± 123.6</td>
<td>1321.8 ± 119.3 ab2</td>
</tr>
<tr>
<td>Total Bout 2 hard run (m)</td>
<td>1172.9 ± 146.5</td>
<td>1210.8 ± 122.9</td>
<td>1234.0 ± 139.1 a</td>
</tr>
<tr>
<td>Total Bout 1 jog (m)</td>
<td>857.9 ± 109.1</td>
<td>828.9 ± 60.2</td>
<td>882.9 ± 71.6 b2</td>
</tr>
<tr>
<td>Total Bout 2 jog (m)</td>
<td>811.0 ± 96.0</td>
<td>809.4 ± 77.1</td>
<td>846.3 ± 75.8 b</td>
</tr>
<tr>
<td>Total Bout 1 walk (m)</td>
<td>254.5 ± 18.1</td>
<td>251.6 ± 17.5</td>
<td>258.4 ± 21.6</td>
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<tr>
<td>Total Bout 2 walk (m)</td>
<td>242.9 ± 24.6</td>
<td>246.6 ± 22.6</td>
<td>246.0 ± 23.6</td>
</tr>
</tbody>
</table>

* Significant difference compared to Control condition ($P < 0.05$). b Significant difference compared to 10 min pre-cooling ($P < 0.05$). 1 Large ES compared to Control condition (d > 0.80). 2 Large ES compared to 10 min pre-cooling (d > 0.80).
**Neuromuscular function**

Significant reductions in post-intervention mean peak torque were apparent during COOL20 sessions compared with COOL10 ($P=0.03$; $d=0.92$) and CONT ($P=0.04$; Table 4.2). In contrast, mid-exercise mean peak torque were significantly greater in COOL20 compared with COOL10 ($P=0.04$; $d=0.83$) and respectively greater than CONT ($P=0.01$; $d=1.74$). Similarly, large ES demonstrate greater mid-exercise mean peak torque following COOL10 as opposed to CONT ($d=1.03$). Mean peak torque post-exercise was significantly higher in COOL20 compared with COOL10 ($P=0.03$; $d=1.48$) and CONT ($P=0.05$; $d=1.44$). No significant differences and trivial to moderate ES ($P=0.08–0.92$; $d=0.07–0.76$) were evident between respective cooling conditions for VA pre-intervention, mid-exercise and post-exercise. However, COOL20 post-intervention VA tended to be reduced compared with COOL10 ($d=0.88$). No significant differences and trivial to moderate ES were apparent for Tpt between conditions at all time points ($P=0.08–0.54$; $d=0.05–0.69$).
Table 4.2. Mean ± SD mean peak torque, time to peak torque and voluntary activation (VA) level for 20 min pre-cooling, 10 min pre-cooling and Control conditions pre-intervention, post-intervention, mid-exercise and post-exercise.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>10 min</th>
<th>20 min</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-Intervention</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Peak Torque (Nm)</td>
<td>155.18 ± 28.17</td>
<td>152.6 ± 17.6</td>
<td>154.2 ± 24.8</td>
</tr>
<tr>
<td>Time to Peak Torque (ms)</td>
<td>99.95 ± 11.66</td>
<td>92.6 ± 17.6</td>
<td>89.3 ± 9.1</td>
</tr>
<tr>
<td>VA Level (%)</td>
<td>75.63 ± 8.80</td>
<td>74.6 ± 6.6</td>
<td>78.3 ± 7.9</td>
</tr>
<tr>
<td><strong>Post-Intervention</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Peak Torque (Nm)</td>
<td>146.89 ± 28.32</td>
<td>153.7 ± 18.5</td>
<td>139.9 ± 23.6</td>
</tr>
<tr>
<td>Time to Peak Torque (ms)</td>
<td>91.85 ± 9.43</td>
<td>102.7 ± 14.9</td>
<td>97.3 ± 13.5</td>
</tr>
<tr>
<td>VA Level (%)</td>
<td>69.31 ± 17.66</td>
<td>77.2 ± 11.0</td>
<td>71.0 ± 8.6</td>
</tr>
<tr>
<td><strong>Mid-Exercise</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Peak Torque (Nm)</td>
<td>125.69 ± 23.71</td>
<td>141.0 ± 17.8</td>
<td>151.4 ± 17.7</td>
</tr>
<tr>
<td>Time to Peak Torque (ms)</td>
<td>92.07 ± 14.47</td>
<td>91.6 ± 15.3</td>
<td>83.9 ± 16.2</td>
</tr>
<tr>
<td>VA Level (%)</td>
<td>66.05 ± 8.91</td>
<td>68.7 ± 15.1</td>
<td>67.2 ± 17.8</td>
</tr>
<tr>
<td><strong>Post-Exercise</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Peak Torque (Nm)</td>
<td>125.26 ± 37.03</td>
<td>138.3 ± 15.6</td>
<td>153.6 ± 19.72</td>
</tr>
<tr>
<td>Time to Peak Torque (ms)</td>
<td>89.38 ± 11.13</td>
<td>95.4 ± 10.2</td>
<td>96.7 ± 14.6</td>
</tr>
<tr>
<td>VA Level (%)</td>
<td>70.21 ± 16.82</td>
<td>70.9 ± 10.0</td>
<td>68.9 ± 11.8</td>
</tr>
</tbody>
</table>

* Significant difference compared to Control condition (P < 0.05).  
† Significant difference compared to 10 min pre-cooling (P < 0.05).  
1 Large ES compared to Control condition (d > 0.80).  
2 Large ES compared to 10 min pre-cooling (d > 0.80).  
* Significant difference compared to pre-intervention values (P < 0.05).  
† Large ES compared to pre-intervention values (d > 0.80).
**Physiological variables**

No significant differences and small to moderate ES ($P= 0.53 – 0.64; d= 0.17 – 0.56$) were present in HR values between all conditions pre- or post-intervention (Figure 4.3A). Whilst there were no significant differences between all conditions for mean Bout 1 HR responses ($P= 0.19 – 0.44$), COOL20 values tended to be reduced compared with COOL10 (d= 0.88) and CONT (d= 0.99). No significant differences in HR values were evident between cooling durations during the mid-protocol recovery period ($P= 0.08 – 0.14$); though large ES indicated reduced values in the COOL20 condition compared with COOL10 (d= 1.27) and CONT (d= 1.59). No significant differences and small to moderate ES ($P= 0.30 – 0.80; d= 0.26 – 0.54$) were apparent between conditions for mean Bout 2 HR responses. Significant differences and large ES indicated lower $T_c$ values following COOL20 compared with COOL10 ($P= 0.02; d= 1.32$) and CONT ($P= 0.03; d= 1.16$) immediately post intervention (Figure 4.3B). $T_c$ remained lower for the entirety of the exercise protocol during COOL20 compared with CONT ($P= 0.003 – 0.04; d= 0.82 – 1.20$). Moreover, large ES also indicated lower $T_c$ values during the COOL10 sessions than CONT (d= 0.80 – 1.10). No significant differences in $T_c$ were evident between cooling durations throughout the exercise protocol ($P= 0.18 – 0.95$).

Significant differences and large ES indicate lower $T_{sk}$ throughout the intervention period following COOL20 cooling compared with CONT ($P= 0.001; d= 3.89 – 7.47$) (Figure 4.3C). Similarly, large ES was observed for lower $T_{sk}$ for the entirety of the cooling application within COOL10 sessions compared with CONT ($P= 0.01 – 0.03; d= 1.72 – 7.60$). Both pre-cooling durations significantly reduced post-intervention heat storage compared with CONT ($P= 0.000 – 0.001; d= 3.66 – 8.18$) (Figure 4.3D). Further, durational effects were evident
with a large ES indicating a greater decrease in heat storage post-intervention following COOL20 compared with COOL10 ($P = 0.64$; $d = 2.44$). Heat storage remained significantly reduced at 35 min in COOL20 trials ($P = 0.03$), with large ES demonstrating lower heat storage with both pre-cooling conditions compared with control during the mid-exercise rest period ($d = 1.12 – 1.64$). Following the reapplication of cooling stimulus, heat storage was significantly lower with both pre-cooling durations at 50 min ($P = 0.001 – 0.004$; $d = 3.34 – 3.37$) compared with CONT. COOL20 displayed a reduced heat storage compared with COOL10 ($P = 0.07$; $d = 1.41$) and CONT at 85 min ($P = 0.0001$; $d = 2.48$). Finally, a large ES indicates a reduced heat storage with COOL10 compared with CONT immediately post-exercise ($P = 0.12$; $d = 0.96$).
Figure 4.3. A Mean ± SD core temperature, B skin temperature, C heart rate, and D body heat storage for 20 min pre-cooling, 10 min pre-cooling and Control conditions.

\* Significant difference between COOL20 and Control conditions (P < 0.05). \# Significant difference between COOL20 and COOL10 conditions (P < 0.05). \^ Significant difference between COOL10 and Control conditions (P < 0.05). \_ Large ES between COOL20 and Control conditions (d > 0.80). \_\_ Large ES between COOL20 and COOL10 conditions (d > 0.80). \_\_\_ Large ES between COOL10 and Control conditions (d > 0.80).
No significant differences and trivial to small ES were evident for pre-exercise USG values during COOL20 cooling (1.015 ± 0.006), COOL10 cooling (1.015 ± 0.007) and CONT trials (1.016 ± 0.004; \( P = 0.66 – 0.89; d = 0.10 – 0.29 \)). Mean changes in pre- to post-exercise body mass were significantly less following pre-cooling (COOL20= 1.8 ± 0.3; COOL10= 2.0 ± 0.3) compared with CONT (2.3 ± 0.4; \( P = 0.003 – 0.013; d = 1.17 – 2.12 \)). Although not significant (\( P = 0.19 \)), a large ES indicates sweat loss induced changes in body mass to be less with COOL20 than COOL10 (d= 1.01).

**Venous and capillary blood variables**

No significant differences (\( P = 0.06 – 1.00 \)) were detected in capillary blood measures for pH, glucose, [La\(^{-}\)], HCO\(_{3}\) pre- and post-exercise (Figure 4.4). Mid-exercise [La\(^{-}\)] concentrations were decreased with COOL20 compared with COOL10 (d= 1.07) and CONT (d= 1.43). This trend continued throughout, with [La\(^{-}\)] values higher in CONT than COOL10 (d= 0.82) and COOL20 (d= 2.13) post-exercise. No significant differences and trivial to moderate ES (d= 0.04 – 0.53; Table 4.3) were evident for pre-exercise CK, CRP, TEST, INS and CORT concentration. Significant differences and large ES indicate reduced CK post-exercise with COOL20 compared with COOL10 (\( P = 0.03; d = 1.02 \)) and CONT (\( P = 0.04; d = 1.49 \)). Large ES denote lesser CK post-exercise under COOL10 than CONT conditions (d= 1.13). Further, pre- to post-exercise change in CK was attenuated with COOL 20 (\( P = 0.03; d = 1.51 \)) and COOL10 (\( P = 0.21; d = 1.14 \)) compared with CONT. Similarly, relative to total shuttle run distance completed, pre- to post-exercise changes in CK were lower following COOL20 (0.02 ± 0.01; \( P = 0.05; d = 1.66 \)) and COOL10 (0.03 ± 0.03; \( P = 0.09; d = 1.19 \)) than CONT (0.08 ± 0.07). Although not significant, a large ES indicated increased post-exercise CORT concentrations in the COOL20 trial compared with CONT (\( P = 0.25; d = 0.88 \)), with this large
trend maintained when compared relative to shuttle running workload completed in COOL20 (0.07 ± 0.04) and CONT (0.04 ± 0.04; \( P = 0.27; d = 1.02 \)). No significant differences and trivial to moderate trends were observed in all remaining venous blood variables (\( P = 0.10 – 0.97; d = 0.03 – 0.64 \)).

Perceptual measures

No significant differences and trivial to small ES (\( P = 0.29 – 0.96; d = 0.001 – 0.38 \)) were apparent for mean RPE values between COOL20 (4.8 ± 0.6), COOL10 (4.8 ± 0.6) and CONT (5.0 ± 0.9). Significant differences and large ES represent a reduced mean TSS value with COOL20 (5.2 ± 0.5) compared with COOL10 (6.0 ± 0.4; \( P = 0.02; d = 2.29 \)) and CONT (6.3 ± 0.6; \( P = 0.00; d = 3.14 \)). Mean TSS ratings during COOL10 sessions were largely reduced compared with CONT (d= 1.16).
Figure 4.4. Mean ± SD capillary blood comparison of anaerobic metabolites between 20 min pre-cooling, 10 min pre-cooling and Control conditions.

1 Large ES between COOL20 and Control conditions (d > 0.80). 2 Large ES between COOL20 and COOL10 conditions (d > 0.80). 3 Large ES between COOL10 and Control conditions (d > 0.80).
Table 4.3. Mean ± SD biochemical data between 20 min pre-cooling, 10 min pre-cooling and Control conditions between interventions and over time.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>10 min</th>
<th>20 min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>238.3 ± 137.4</td>
<td>213.0 ± 76.0</td>
</tr>
<tr>
<td>CK (U L⁻¹)</td>
<td>Post</td>
<td>585.1 ± 368.3</td>
<td>365.1 ± 127.9</td>
</tr>
<tr>
<td></td>
<td>∆</td>
<td>346.9 ± 312.0</td>
<td>152.1 ± 135.8</td>
</tr>
<tr>
<td>CRP (mg L⁻¹)</td>
<td>Pre</td>
<td>3.00 ± 4.94</td>
<td>2.86 ± 4.75</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>3.23 ± 5.01</td>
<td>3.04 ± 4.76</td>
</tr>
<tr>
<td></td>
<td>∆</td>
<td>0.23 ± 0.44</td>
<td>0.18 ± 0.13</td>
</tr>
<tr>
<td>INS (µL mL⁻¹)</td>
<td>Pre</td>
<td>5.94 ± 1.61</td>
<td>5.73 ± 1.14</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>5.09 ± 1.82</td>
<td>5.33 ± 1.63</td>
</tr>
<tr>
<td></td>
<td>∆</td>
<td>-0.74 ± 1.87</td>
<td>-0.35 ± 1.74</td>
</tr>
<tr>
<td>TEST (ng dL⁻¹)</td>
<td>Pre</td>
<td>379.1 ± 84.3</td>
<td>404.8 ± 63.3</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>494.0 ± 156.4</td>
<td>491.6 ± 59.3</td>
</tr>
<tr>
<td></td>
<td>∆</td>
<td>215.0 ± 1.94.5</td>
<td>290.1 ± 201.0</td>
</tr>
<tr>
<td>CORT (nmol L⁻¹)</td>
<td>Pre</td>
<td>330.4 ± 98.4</td>
<td>325.8 ± 85.2</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>545.4 ± 198.6</td>
<td>615.9 ± 146.7</td>
</tr>
<tr>
<td></td>
<td>∆</td>
<td>114.9 ± 110.0</td>
<td>86.9 ± 39.3</td>
</tr>
</tbody>
</table>

* Significant difference compared to Control condition (P < 0.05).  
  b Significant difference compared to 10 min pre-cooling (P < 0.05).  
  1 Large ES compared to Control condition (d > 0.80).  
  2 Large ES compared to 10 min pre-cooling (d > 0.80).
Discussion

Findings from the present study indicate the possible existence of a duration effect of mixed-method pre-cooling on ensuing exercise performance and physiological responses. Increasing evidence demonstrates dose-specific effects of pre-cooling (surface area coverage or temperature) on both physiological and performance outcomes of exercise in the heat (Castle et al., 2006; Daanen et al., 2006; Bogerd et al., 2010; Minett et al., 2011). Similarly, these results highlight the benefits of a longer pre-cooling duration (up to 20 min) when using mixed-method techniques by providing greater augmentation of performance and blunting of physiological loads. An apparent maintenance of post-exercise MVC following pre-cooling in the heat may demonstrate sustained neuromuscular function, despite higher shuttle-running distances completed, and a similar change in VA. Accordingly, the observed performance improvements and greater physiological changes apparent with the longer cooling duration (COOL20 > COOL10 > CONT) may implicate greater maintenance of endogenous thermal control, with an associated preservation of neuromuscular force production possibly facilitating subsequent exercise performance benefits.

Effective pre-cooling increases heat storage reserve (Figure 4.3D), allowing athletes to better accommodate high levels of metabolic and environmental heat stress, elongating periods of higher exercise intensity (Marino, 2002; Quod et al., 2006; Duffield, 2008). This is demonstrated in the current data with higher self-paced, sub-maximal running distances maintained throughout the exercise protocol. In accordance with previous investigations (Duffield & Marino, 2007; Duffield et al., 2009d; Minett et al., 2011), greater shuttle-running distances were covered during the longest exposure trial (COOL20; Table 4.1; Figure 4.2B). Further, COOL20 aided repeat-sprint ability and maintenance of sprint times during Bout 2
(Table 4.1, Figure 4.2A). Whilst these findings support previously documented benefits of pre-cooling for self-paced intermittent-sprint performance in the heat (Castle et al., 2006; Duffield & Marino, 2007; Duffield et al., 2009d; Minett et al., 2011), minimal differences between COOL10 and CONT (Table 4.1; Figure 4.2A; Figure 4.2B) suggest the importance of cooling duration with this method for attaining ergogenic effects. Accordingly, the reduced cooling exposure of the COOL10 condition (10 min), and to a lesser extent the 5 min mid-exercise reapplication, may have been of insufficient duration to achieve explicit performance benefits. Similarly beneficial effects of increasing dose by either surface area coverage (Minett et al., 2011), temperature (Bogerd et al., 2010) or cooling duration as shown here highlight the requirement of mixed-method pre-cooling intervals greater than 10 and up to 20 min to evoke beneficial performance outcomes (Castle et al., 2006; Duffield & Marino, 2007; Duffield et al., 2009d).

Despite the growing consensus over the benefits of pre-cooling for intermittent-sprint exercise in the heat, care is required to ensure desirable dose-responses are achieved. Given the relationship between reduced muscle temperatures and suppressed neuromuscular recruitment and contractile properties (Racinais & Oksa, 2010), it could be suggested that the durational effects of cooling application may account for the observed reduction in MVC immediately post COOL20 application (Table 4.2). However, this does not explain the observed slower Tpt post-intervention under COOL10 conditions otherwise absent following COOL20 cooling (Table 4.2). Interestingly, Peiffer et al. (2009b) report no difference in muscle function between post-exercise cooling durations regardless of changes in muscle temperature. Methodological discrepancies prevent direct comparison with the current data, yet findings of acute impairment in muscle function immediately following pre-cooling is not surprising and may explain previously reported detrimental effects of cooling in short-
duration, high-intensity exercise (Marino, 2002; Quod et al., 2006; Duffield, 2008). Nevertheless, such a finding emphasises the importance of post-cooling warm-up procedures to avoid possible initial ergolytic effects of temperature inhibited voluntary force production and ensuing exercise performance as observed by Skein et al. (2012). Accordingly, the combined effects of pre-cooling followed by an adequate warm-up may improve neuromuscular contractile function and perceptual readiness for exercise, while still attenuating cardiovascular and thermoregulatory strain associated with exercise in the heat.

Despite initial reduction in MVC, longer pre-cooling duration maintained voluntary force during and following exercise. Previous research suggests a suppression of neuromuscular drive under heat stress may be attributable to a centrally mediated impairment of VA (Nybo & Nielsen, 2001a; Morrison et al., 2004; Todd et al., 2005; Thomas et al., 2006). This response was not present following COOL20, with greater heat removal possibly facilitating the maintenance of MVC mid- and post-exercise (Table 4.2). However, similar $T_c$ irrespective of pre-cooling duration mid- and post-exercise (Figure 4.3B), contradict the demonstrated association between a reduced MVC and elevated thermal loads as previously shown with passive heating/cooling techniques (Morrison et al., 2004; Thomas et al., 2006). Further, the lack of inter-trial differences in VA, even though enhanced MVC and self-paced running workloads were achieved with more extensive pre-cooling, make it difficult to distinguish performance alterations as of CNS modulation alone. Whilst a higher force production following COOL20, without conditional differences in VA, suggests the interaction of peripheral mechanisms, similar Tpt between conditions post-exercise demonstrates the maintenance of contractile function below the neuromuscular junction. Alternatively, it could be postulated that dose-dependent responses of mixed-method pre-cooling duration result in sustained reduction of $T_{sk}$, TSS and the same absolute $T_c$ for a
greater workload highlighting the maintenance of voluntary force in the heat (Schlader et al., 2011). Nevertheless, such a response remains speculative given the inconclusive relationship between cooling duration, physiological and perceptual responses and the maintenance of MVC for a similar change in VA.

To explain reduced exercise performance in the heat, CNS fatigue in hot conditions has been hypothesised to engage a complex interaction of feedback and/or feed-forward controls (Nybo & Nielsen, 2001a; Marino, 2004; Tucker et al., 2004; Nybo, 2008). The suppression of coexisting central, peripheral and perceptual strain with longer pre-cooling duration may have culminated in the retention of neuromuscular function and subsequent preservation of MVC mid- and post-exercise, despite increased work performed (Tucker et al., 2004; Duffield et al., 2010). Thus, it is possible that pre-cooling may aid in the sustained recruitment of exercising musculature in the heat (Kay et al., 2001; Tucker et al., 2004), presenting the potential for attainment of higher self-paced running workloads and preventing the reduction in repeat-sprint activity (Duffield, 2008). Regardless of the specific mechanism/s, discrepancies in voluntary force production and exercise performance outcomes demonstrated using this step-wise approach to cooling highlight possible alterations in feedback and/or feed-forward processes that may be altered with sufficient mixed-method pre-cooling duration. Hence it is possible that performance benefits presented here may owe to the duration specific application of the cooling stimulus, and subsequent reductions in physiological (HR, \( T_c \) and \( T_{sk} \)) and perceptual loads (TSS) assisting to maintain neuromuscular function (MVC) and extend the period of desired exercise intensity in hot conditions (Duffield, 2008).
Both pre-cooling durations attenuated thermoregulatory demands to exercise-induced heat stress, with reductions in $T_c$ and $T_{sk}$ providing increased heat storage reserve. Nevertheless, the longer the mixed-method pre-cooling was applied (COOL20 > COOL10 > CONT), the greater the reduction in thermal stress remained throughout the exercise protocol (Figure 4.3). Alterations to the thermal gradient may have precluded concurrent demands for blood flow to the active musculature as well as the periphery for heat dissipation (González-Alonso et al., 1997). Accordingly, centralised blood volume is maintained, easing the cardiovascular challenges associated with exercise in the heat (Wendt et al., 2007). Further, greater heat removal with more extensive pre-cooling reduced sweat loss alterations in blood volume, preventing cardiovascular drift and leaving any work related increases in HR significantly attenuated (Marino, 2002). Differences between inter-trial sweat loss (~500 mL) are comparable to previous finding (Kay et al., 1999; Arngrímsson et al., 2004; Duffield et al., 2010; Minett et al., 2011) and it is unknown if such volumes are sufficient to explain these performance outcomes alone.

Given the dose-specific physiological responses to cooling duration and increasing self-paced work rates, consideration of acute biochemical reactions may prove beneficial. The lack of conditional discrepancies in anaerobic metabolite and muscle damage markers previously reported are largely reiterated here (Castle et al., 2006; Duffield & Marino, 2007). However, the reduction in [La$^-$] mid- and post-exercise with longer cooling duration suggests a lower dependence on glycolytic energy sources as heat stress is reduced throughout COOL20 trials (Young et al., 1985). Interestingly, marked alteration in biochemical responses to muscle damage and stress demonstrate divergent reactions to mixed-method cooling durations relative to shuttle running distances covered. Whilst elevated CORT post-exercise with COOL20 may reflect a compensatory stress response to the increased work performed
(Minett et al., 2011), CK were attenuated with longer mixed-method cooling applications (Table 4.3). Considering the higher workloads completed with mixed-method pre-cooling, it is unlikely that a lesser CK concentration could be attributed to a reduction in exercise-induced muscle damage. Rather, it is possible that lessening thermal demands with COOL10 and COOL20 may facilitate a greater maintenance of cellular integrity, resulting in a reduced CK efflux and lower circulatory concentrations (Alzeer et al., 1997). Although the acute performance effects of pre-cooling in these data are clear, the potential effects of a higher catabolic state on subsequent adaptation and recovery present an area for future study.

In summary, mixed-method pre-cooling duration appears important to subsequent suppression of physiological and perceptual responses to exercise induced heat stress. Accordingly, enhanced thermoregulatory control may facilitate the maintenance of sprint times and self-selected sub-maximal efforts. Most pertinent, however, was the dose effect demonstrated, with the incremental mixed-method pre-cooling durations resulting in different levels of physiological and performance responses. Consequently, the greater reduction in heat stress experienced during the COOL20 trial may have aided in the maintenance of MVC and improved running workloads completed. Whilst these findings provide evidence for the importance of duration of pre-exercise cooling for ensuing exercise performance in hot conditions, consideration for individual logistics and demands should be considered prior to field-based application.
Mixed-Method Pre-Cooling Reduces Physiological Demand without Improving Performance of Medium-Fast Bowling in the Heat

As published in the *Journal of Sports Sciences*
Abstract

This study examined physiological and performance effects of pre-cooling on medium-fast bowling in the heat. Ten, medium-fast bowlers completed two randomised trials involving either cooling (mixed-methods) or control (no cooling) interventions before a 6-over bowling spell in 31.9 ± 2.1°C and 63.5 ± 9.3% relative humidity. Measures included bowling performance (ball speed, accuracy and run-up speeds), physical characteristics (global positioning system monitoring and counter-movement jump height), physiological (heart rate, core temperature, skin temperature and sweat loss), biochemical (serum concentrations of damage, stress and inflammation) and perceptual variables (perceived exertion and thermal sensation). Mean ball speed (114.5 ± 7.1 vs. 114.1 ± 7.2 km h⁻¹; \(P=0.63; d=0.09\)), accuracy (43.1 ± 10.6 vs. 44.2 ± 12.5 AU; \(P=0.76; d=0.14\)) and total run-up speed (19.1 ± 4.1 vs. 19.3 ± 3.8 km h⁻¹; \(P=0.66; d=0.06\)) did not differ between pre-cooling and control respectively; however 20-m sprint speed between overs was 5.9 ± 7.3% greater at Over 4 after pre-cooling (\(P=0.03; d=0.75\)). Pre-cooling reduced skin temperature after the intervention period (\(P=0.006; d=2.28\)), core temperature and pre-over heart rates throughout (\(P=0.01–0.04; d=0.96–1.74\)) and sweat loss by 0.4 ± 0.3 kg (\(P=0.01; d=0.34\)). Mean rating of perceived exertion and thermal sensation were lower during pre-cooling trials (\(P=0.004–0.03; d=0.77–3.13\)). Despite no observed improvement in bowling performance, pre-cooling maintained between-over sprint speeds and blunted physiological and perceptual demands to ease the thermoregulatory demands of medium-fast bowling in hot conditions.


**Introduction**

Medium-fast bowling in cricket is a dynamic and physically taxing activity that requires combined tactical and technical proficiency for competitive success (Woolmer et al., 2008). Specifically, medium-fast bowling in first-class cricket involves repetitive high-intensity bouts (n= 50 – 56 efforts h⁻¹) separated by extended periods of predominantly lower-intensity fielding activities, with players covering ~22 – 24 km in a full day’s play (Petersen, et al., 2010b, 2011). Compounding these physical demands, seasonal scheduling of competition in hot and humid environments magnifies physiological and perceptual demands as effective heat transfer is reduced (Wendt et al., 2007). Subsequently, exercise in hot conditions can increase thermoregulatory, cardiovascular and metabolic demands (Morris et al., 2000), while decreasing fluid volume (González-Alonso, 1998), neuromuscular function (Kay et al., 2001) and exercise performance (Drust et al., 2005). These larger physiological and perceptual demands, along with anticipation of ensuing challenges to thermoregulation, reduce exercise intensity in the heat (Tucker, 2009). Accordingly, hot/humid conditions can increase thermal strain (Gore et al., 1993) to the detriment both of medium-fast bowling performance (Devlin et al., 2001) and health status (Driscoll et al., 2008; Finch & Boufous, 2008).

Pre-cooling strategies have been promoted to improve intermittent-sprint exercise in the heat (Castle et al., 2006; Duffield & Marino, 2007; Minett et al., 2011). Increased heat storage reserves achieved with pre-cooling offset metabolic and environmental heat gain, protecting neuromuscular function to prolong higher self-selected exercise intensities (Duffield et al., 2010; Skein et al., 2012). While the ecological validity of cold-water immersion in the field is accompanied by difficulties of implementation (Marino, 2002), the combination of multiple part-body cooling apparatus offers viable alternatives for pre-cooling in the field.
(Quod et al., 2008; Duffield et al., 2009d; Ross et al., 2011). Provided sufficient dosage (surface area coverage, duration and temperature) of cooling stimulus is applied (Duffield, 2008; Bogerd et al., 2010; Minett et al., 2011), a practical, mixed-method approach to pre-cooling could provide ergogenic assistance to medium-fast bowling performance, and/or reduce the physiological and perceptual loads encountered with prolonged bowling spells in the heat.

Given the importance of medium-fast bowling to team success (Wormgoor et al., 2010) and the regularity of elite-standard competition in hot conditions (Petersen et al., 2010a), pre-cooling is a possible protective strategy for the maintenance or improvement of medium-fast bowling performance in the heat. However, while pre-cooling might aid intermittent-sprint exercise, (Castle et al., 2006; Duffield & Marino, 2007; Duffield et al., 2009d; Minett et al., 2011), limited data are available to evaluate its effects on sports-specific skill performance (Hornery et al., 2007a). Further, mixed-method pre-cooling techniques developed under laboratory conditions are untested in task-representative settings (Duffield et al., 2009d). Hence, the aim of this investigation was to determine physiological, perceptual and performance effects of mixed-method pre-cooling on a 6-over spell of medium-fast bowling in the heat. Pre-cooling was hypothesised to improve performance and reduce the physiological demand of medium-fast bowling in the heat.
Methods

Participants

Ten, well-trained, male, medium-fast bowlers were recruited for this study (mean ± standard deviation: age 23 ± 8 y; stature 189.8 ± 8.8 cm; body mass 84.9 ± 12.6 kg). Participants were senior-level club cricketers or junior state-based players and reported ≥ 5 training and competition days on a weekly basis. After explanation of experimental risks and procedures, all participants provided written and verbal informed consent and ethics approval was granted by the Ethics in Human Research Committee of the University.

Overview

A randomised, repeated-measures cross-over design was used to examine the effects of a field-based pre-cooling intervention on performance, physiological and perceptual responses during a 6-over medium-fast bowling spell in hot conditions. Participants were accustomed to all equipment and procedures before completing two standardised testing sessions separated by 3-5 days. All testing was completed during the in-season phase of competition. Sessions were identical, with only the pre-cooling intervention altered throughout. Participants completed two respective trials, including a control session (no pre-cooling) and a 20-min pre-cooling session (mixed-method pre-cooling). Each testing session involved a 6-over bowling spell based on an adaptation of the Cricket Australia-Australian Institute of Sport fast bowling skills test (Portus et al., 2010). All data collection was conducted outdoors in mean ± standard deviation environmental conditions of 31.9 ± 2.1°C and 63.5 ± 9.3% relative humidity. Participants abstained from strenuous exercise and alcohol 24 h before and all caffeine and food substances 3 h before each testing session. Physical activity records and
food diaries were documented for 24 h leading into the initial session and repeated for the remaining trial.

**Exercise protocol**

All testing was completed at a cricket-specific outdoor training facility on a centre-square turf wicket. The exercise protocol involved a modified version of that previously described by Duffield et al. (2009a). Before commencement, participants completed a standardised 10-min warm-up consisting of jogging, sprinting and 10 practice deliveries, gradually increasing bowling speed to match intensity. Participants then performed a 6-over bowling spell at match intensity based on the Cricket Australia-Australian Institute of Sport fast bowling skills test, whereby players aimed to bowl deliveries of pre-determined line (right- and left-handed batsmen) and length (short, good length, and full deliveries) to replicate skill-based match requirements. Bowling in pairs and alternating overs, participants aimed to hit specific targets as instructed before each delivery that were highlighted on a 20 x 20-cm vertical grid positioned on the popping crease at the batsmen’s end. The order of delivery type was standardised for each bowler as per the 4-over Cricket Australia-Australian Institute of Sport test, with the initial two overs replicated to extend the bowling spell in overs five and six.

Each bowling spell was completed using a new regulation four-piece (156 g) cricket ball (Turf White, Kookaburra, Melbourne, Australia). Participants completed physical activities between overs to simulate match demands, including walking 10 m to correspond with each delivery and sprinting 20 m on the 2nd and 4th balls of each over. All fluid intake was restricted during the bowling spell.
Pre-cooling intervention

Pre-cooling involved a modified mixed-method approach as previously detailed (Minett et al., 2011). In brief, participants were cooled for 20 min in a seated position using a cold, wet towel placed over the head, neck and shoulders, ice-vest covering the torso (Arctic Heat, Brisbane, Australia), their non-bowling hand was immersed to the wrist in cold water (9.0 ± 0.5°C) and ice-packs were applied to the quadriceps muscle of each leg (Techni Ice, Frankston, Australia). Ice-vests and ice-packs were stored at -20°C, while cold, wet towels were soaked in cold water (5.0 ± 0.5°C) before application. Participants sat passively for 20 min and received no cooling during control trials.

Performance Measures

Bowling performance was determined throughout the 6-over spell (36 balls) according to ball speed and accuracy. A calibrated radar gun (Stalker ATS, Applied Concepts, Texas, USA) positioned approximately 5 m behind the bowlers arm was used to assess ball speed at the point of release. Bowling accuracy was assessed according to the Cricket Australia-Australian Institute of Sport grid-based accuracy system whereby each ball was numerically rewarded for its proximity to a pre-designated target (Portus et al., 2010). An infra-red timing system (Speed-light, Swift, Wacol, Australia) determined overall and final 5-m run-up speeds.

Before and after exercise, counter-movement jump height were assessed using a linear position transducer (G1706374B; Fitness Technology, Adelaide, Australia) interfaced with Ballistic Measurement System software (Fitness Technology, Adelaide, Australia).
Participants completed a maximal, 10-repetition counter-movement jump protocol with the position transducer attached to a dowel rod across the shoulders to minimise arm swing and standardise jump technique. Linear position transducers are reported as a reliable (intra-class correlation coefficient= 0.721 – 0.982; coefficient of variation= 2.1 – 11.7%) and valid (r= 0.861 – 0.959) measure of jump performance variables (Cronin, Hing & McNair, 2004).

For the duration of the bowling protocol, participants were fitted with an SPI Elite (GPSports, Canberra, Australia) global positioning system unit (1 Hz), harnessed between the scapulae at the base of the cervical spine. Data were downloaded (Team AMS, GPSports, Canberra, Australia) for analysis at the conclusion of each session and classified as either low-intensity activity (<7.0 km·h⁻¹), moderate-intensity activity (7.0 – 14.4 km·h⁻¹), high-intensity activity (>14.4 km·h⁻¹) and very-high-intensity activity (>20 km·h⁻¹) (Duffield et al., 2009b). Coutts and Duffield (2010) report the mean coefficient of variation of this model to be 0.5 – 3.2% for distances covered and 0.8 – 20% for pre-defined speed zones and peak speeds.

*Physiological measures*

A mid-stream urine sample was collected before each session for the assessment of urine specific gravity (Refractometer 503, Now. Nippon Optical, Works Co, Tokyo, Japan). Nude body mass was assessed before and after exercise with calibrated scales accurate to 0.05 kg (UC-321, A & D, Adelaide, Australia) to indicate non-urinal fluid loss. Participants wore a heart rate monitor throughout (FS1, Polar Electro Oy, Kempele, Finland) and ingested a telemetric core temperature capsule (VitalSense, Mini Mitter, Bend, USA) 5 h before each session to ensure passage into the gastro-intestinal tract. Heart rate and core temperature
responses were recorded before the intervention, at 10 min increments during the intervention period, and before and after each over. Measures of skin temperature were recorded with an infra-red thermometer (ThermoScan 3000, Braun, Kronberg, Germany) (Burnham, McKinley & Vincent, 2006) at three sites (sternum, mid-forearm, and medial calf) and used to calculate mean-weighted skin temperature as per Burton (1934). Skin temperature was measured before the intervention, every 10 min during the intervention protocol, and before and after exercise.

**Blood collection and biochemical analysis**

Indirect measures of muscle damage, inflammation and stress responses to pre-cooling were assessed using venous blood samples drawn before and 30 min after exercise. Samples were collected using serum separator tubes (Monovette, Sarstedt, Numbrecht, Germany) and allowed to clot at room temperature before centrifugation (10 min at 4000 rpm). Serum was separated and stored at -20°C until analyses. Creatine kinase concentration was determined using an enzymatic method and bichromatic rate technique (co-efficient of variation= 3.0%), while C-reactive protein was assessed according to the particle-enhanced turbidimetric-immunoassay methods (co-efficient of variation= 3.8%; Dimension Xpand spectrophotometer, Dade Behring, Atlanta, USA). Insulin, testosterone and cortisol were measured using a solid-phase, competitive chemiluminescent enzyme immunoassay (co-efficient of variation= 2.8%, 4.3%, 2.1% respectively; Immulite 2000, Diagnostic Products Corp., Los Angeles, USA).
Perceptual measures

Rating of perceived exertion and thermal sensation were monitored as per the Borg CR-10 scale (0= nothing at all – 10= maximal) and an 8-point Likert scale (0= unbearably cold – 8= unbearably hot) respectively. Rating of perceived exertion and thermal sensation values were recorded at 10-min intervals during pre-cooling and after each over.

Statistical Analysis

Data are reported as mean ± standard deviation. A repeated-measures analysis of variance (ANOVA) compared treatments, with a Fisher’s LSD applied for post hoc analysis. Significance was accepted as $P < 0.05$. Results were analysed with the Statistical Package for Social Sciences (SPSS v 17.0, Chicago, USA). Further, the magnitudes of change between conditions were calculated according to standardised mean differences (Cohen’s d effect size), whereby an effect size of < 0.2 is classified as ‘trivial’, 0.2 – 0.4 as ‘small’, 0.5 – 0.7 as ‘moderate’ and > 0.8 as ‘large’ effects.

Results

Performance

Mean ± standard deviation ball speed and bowling accuracy are presented in Table 5.1. Overall total run-up and final 5-m run-up speeds are presented in Figure 5.1. There were no differences and only trivial-to-small effect sizes for mean ball speed (pre-cooling 114.5 ± 7.1 km h$^{-1}$ vs. control 114.1 ± 7.2 km h$^{-1}$; $P= 0.63$; d= 0.09) and bowling accuracy (pre-cooling 43.1 ± 10.6 AU vs. control 44.2 ± 12.5 AU; $P= 0.76$; d= 0.14). Mean and peak ball speeds for
the respective 6 overs were not different between conditions ($P= 0.12 – 1.00$), with only trivial-to-small effect sizes demonstrated throughout ($d= 0.05 – 0.31$). There were no differences between conditions and small-to-moderate effect sizes for bowling accuracy scores attained during each over ($P= 0.09 – 0.71; d= 0.32 – 0.78$). Further, there were no differences and only trivial effect sizes apparent in overall total run-up speed (pre-cooling $19.08 \pm 4.10 \text{ km h}^{-1}$ vs. control $19.25 \pm 3.81 \text{ km h}^{-1}; P= 0.66; d= 0.06$) and final 5-m run-up speed (pre-cooling $21.70 \pm 2.70 \text{ km h}^{-1}$ vs. control $21.56 \pm 2.32 \text{ km h}^{-1}; P= 0.31; d= 0.08$). Similarly, run-up speeds did not differ at any stage of the bowling spell ($P= 0.31 – 1.00; d= 0.001 – 0.19$).

All time-motion measures were unchanged between conditions during the bowling spell ($P= 0.31 – 1.00; d= 0.01 – 0.37; \text{ Table } 5.2$), though mean peak sprint speed was greater after Over 4 during pre-cooling trials ($P= 0.03; d= 0.75; \text{ Table } 5.2$). There were no differences and only trivial-to-moderate effect sizes observed for all remaining between-over peak sprint-speed variables ($P= 0.13 – 0.98; d= 0.02 – 0.63$). Further, there were no differences ($P= 0.22 – 0.50; d= 0.18 – 0.45$) apparent for counter-movement jump height before (pre-cooling $39.6 \pm 7.3 \text{ cm}$ vs. control $40.6 \pm 8.1 \text{ cm}$) or after the bowling spell (pre-cooling $41.8 \pm 6.8 \text{ cm}$ vs. control $39.3 \pm 8.3 \text{ cm}$).
Table 5.1. Mean ± standard deviation ball speed, peak ball speed and bowling accuracy per over during a 6-over spell.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Over</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bowling Performance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean speed (km(^{-1}))</td>
<td>Control</td>
<td>114.8±6.8</td>
<td>114.5±6.1</td>
<td>114.8±5.6</td>
<td>114.1±5.8</td>
<td>113.5±5.9</td>
<td>113.6±6.7</td>
</tr>
<tr>
<td></td>
<td>Pre-cool</td>
<td>114.4±6.3</td>
<td>115.8±6.8</td>
<td>115.6±6.6</td>
<td>114.3±6.6</td>
<td>113.9±6.5</td>
<td>114.1±7.4</td>
</tr>
<tr>
<td>Peak speed (km(^{-1}))</td>
<td>Control</td>
<td>116.4±6.2</td>
<td>117.1±5.9</td>
<td>116.9±5.8</td>
<td>116.0±6.2</td>
<td>115.8±6.6</td>
<td>116.0±6.3</td>
</tr>
<tr>
<td></td>
<td>Pre-cool</td>
<td>117.3±6.3</td>
<td>118.3±6.7</td>
<td>118.3±7.0</td>
<td>117.2±7.1</td>
<td>116.7±7.2</td>
<td>116.8±7.2</td>
</tr>
<tr>
<td>Mean accuracy (AU)</td>
<td>Control</td>
<td>46.8±17.3</td>
<td>48.9±21.4</td>
<td>39.4±16.2</td>
<td>43.1±16.0</td>
<td>45.1±23.2</td>
<td>44.4±20.0</td>
</tr>
<tr>
<td></td>
<td>Pre-cool</td>
<td>39.9±15.0</td>
<td>44.1±20.0</td>
<td>48.2±15.7</td>
<td>39.2±18.7</td>
<td>37.8±19.0</td>
<td>54.8±18.4</td>
</tr>
</tbody>
</table>
Table 5.2. Mean ± standard deviation time-motion analysis of selected movement patterns, distances covered and peak sprint speed achieved between overs during a 6-over bowling spell.

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Pre-cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance (m)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4328 ± 707</td>
<td>4336 ± 666</td>
</tr>
<tr>
<td>Very-high-intensity activity</td>
<td>442 ± 287</td>
<td>425 ± 299</td>
</tr>
<tr>
<td>High-intensity activity</td>
<td>888 ± 230</td>
<td>866 ± 223</td>
</tr>
<tr>
<td>Moderate-intensity activity</td>
<td>461 ± 75</td>
<td>476 ± 114</td>
</tr>
<tr>
<td>Low-intensity activity</td>
<td>2537 ± 411</td>
<td>2568 ± 316</td>
</tr>
<tr>
<td><strong>Speed (m·s⁻¹)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very-high-intensity activity</td>
<td>5.8 ± 0.5</td>
<td>5.6 ± 0.8</td>
</tr>
<tr>
<td>High-intensity activity</td>
<td>5.2 ± 0.6</td>
<td>5.2 ± 0.5</td>
</tr>
<tr>
<td>Moderate-intensity activity</td>
<td>3.1 ± 0.1</td>
<td>3.01 ± 0.9</td>
</tr>
<tr>
<td>Low-intensity activity</td>
<td>1.0 ± 0.1</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td><strong>Peak sprint speed (km·h⁻¹)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 1</td>
<td>21.7 ± 3.1</td>
<td>22.7 ± 2.1</td>
</tr>
<tr>
<td>Over 2</td>
<td>22.1 ± 2.5</td>
<td>21.9 ± 2.3</td>
</tr>
<tr>
<td>Over 3</td>
<td>21.0 ± 2.5</td>
<td>22.1 ± 2.3</td>
</tr>
<tr>
<td>Over 4</td>
<td>20.9 ± 2.2</td>
<td>22.1 ± 2.2</td>
</tr>
<tr>
<td>Over 5</td>
<td>21.3 ± 2.2</td>
<td>21.3 ± 2.7</td>
</tr>
</tbody>
</table>

* Significant difference between conditions ($P < 0.05$).
Figure 5.1. Overall total run-up and final 5-m run-up speed for each ball of a 6-over spell.
Physiological responses

While core temperature was not reduced during or immediately after the pre-cooling intervention (Figure 5.2A; $P= 0.30 – 0.85$; $d= 0.17 – 0.45$), large effect sizes indicate suppressed core temperature responses throughout the bowling spell ($d= 0.91 – 3.44$). These blunted responses were particularly evident before and after over 1 and after over 5 with core temperature reduced in pre-cooling trials ($P= 0.01 – 0.04$). Resting skin temperature was greater in the pre-cooling condition compared to control (Figure 5.2B; $P= 0.03$; $d= 1.39$). Nevertheless, skin temperature was lower with pre-cooling immediately after the intervention and before commencing the bowling spell ($P= 0.003 – 0.01$; $d= 2.19 – 2.28$). During the intervention, pre-cooling reduced heart rate at 10 min (Figure 5.2C; $P= 0.08$; $d= 0.93$) and 20 min ($P= 0.01$; $d= 1.26$); further, heart rate was reduced before each over for the duration of the bowling spell ($P= 0.01 – 0.04$; $d= 0.96 – 1.74$). Resting urine specific gravity did not differ between conditions (pre-cooling $1.016 ± 0.006$ vs. control $1.016 ± 0.007$; $P= 0.81$; $d= 0.04$), though sweat loss induced changes in body mass incurred during the bowling spell were reduced in pre-cooling trials (pre-cooling $1.46 ± 0.43$ kg vs. control $1.86 ± 0.62$; $P= 0.01$; $d= 0.34$). Finally, there were no differences and only trivial-to-moderate effect sizes detected for all venous blood measures of creatine kinase, C-reactive protein, insulin, testosterone and cortisol before or after the bowling spell (Table 5.3; $P= 0.22 – 0.83$; $d= 0.05 – 0.72$). However, creatine kinase response to the bowling spell was reduced in pre-cooling trials ($P= 0.04$; $d= 1.10$).
Figure 5.2. A Mean ± standard deviation core temperature, B skin temperature and C heart rate between Pre-cooling and Control conditions.

* Significant difference between conditions ($P < 0.05$). # Large ES between conditions (d > 0.80).
Table 5.3. Mean ± standard deviation biochemical comparison between Pre-cooling and Control conditions.

<table>
<thead>
<tr>
<th></th>
<th>Control Before</th>
<th>After</th>
<th>Δ</th>
<th>Pre-cooling Before</th>
<th>After</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creatine Kinase (U L⁻¹)</td>
<td>229 ± 85</td>
<td>389 ± 114</td>
<td>161 ± 132</td>
<td>272 ± 85</td>
<td>355 ± 120</td>
<td>82 ± 54¹</td>
</tr>
<tr>
<td>C-reactive protein (mg L⁻¹)</td>
<td>3.0 ± 3.5</td>
<td>3.5 ± 3.6</td>
<td>0.4 ± 0.9</td>
<td>2.3 ± 1.0</td>
<td>2.7 ± 1.4</td>
<td>0.4 ± 0.8</td>
</tr>
<tr>
<td>Insulin (µL mL⁻¹)</td>
<td>6.9 ± 4.7</td>
<td>6.1 ± 3.2</td>
<td>-0.8 ± 5.9</td>
<td>6.4 ± 2.5</td>
<td>6.5 ± 3.0</td>
<td>0.1 ± 2.0</td>
</tr>
<tr>
<td>Testosterone (ng dL⁻¹)</td>
<td>431 ± 49</td>
<td>449 ± 86</td>
<td>18 ± 81</td>
<td>409 ± 50</td>
<td>445 ± 95</td>
<td>37 ± 65</td>
</tr>
<tr>
<td>Cortisol (nmol L⁻¹)</td>
<td>216 ± 95</td>
<td>408 ± 160</td>
<td>192 ± 121</td>
<td>223 ± 53</td>
<td>441 ± 171</td>
<td>219 ± 175</td>
</tr>
</tbody>
</table>

¹ Significant difference between conditions ($P < 0.05$). ¹ Large ES between conditions ($d > 0.80$).
Figure 5.3. A Mean ± standard deviation rating of perceived exertion and B thermal sensation scale between Pre-cooling and Control conditions.

* Significant difference between conditions ($P < 0.05$). # Large ES between conditions (d > 0.80).
**Perceptual responses**

Results for rating of perceived exertion and thermal sensation are presented in Figure 5.3. Pre-cooling restrained rising rating of perceived exertion as the bowling spell continued, with reductions noted at over 5 (Figure 5.3A; $P=0.004$; $d=0.93$) and over 6 ($P=0.001$; $d=1.81$) respectively. Further, thermal sensation was lower throughout the intervention period and for the duration of the bowling spell in pre-cooling trials (Figure 5.3B; $P=0.003 – 0.03$; $d=1.04 – 4.07$).

**Discussion**

This study examined the effects of pre-cooling on bowling performance, physiological and perceptual responses during a 6-over spell of medium-fast bowling in the heat. Further, we evaluated the efficacy of a practical, mixed-method pre-cooling technique for cricket in a task-representative setting. While pre-cooling had no effect on skill-related bowling performance or run-up speed, an increase in between-over sprint speeds occurred after Over 4. Importantly, pre-cooling improved thermoregulatory control as physiological (heart rate, core temperature, skin temperature and sweat loss) and perceptual strain (rating of perceived exertion and thermal sensation) were reduced throughout the bowling spell. Accordingly, pre-cooling induced suppression of thermal demands provides medium-fast bowlers with small but still potentially worthwhile benefits indicated by a reduced physiological cost for a given bowling effort in hot conditions.

Although the benefits of pre-cooling for intermittent-sprint exercise in the heat have been reported (Duffield, 2008), ensuing effects on sport-specific skill performance are lacking.
(Hornery et al., 2007a). The current data demonstrate trivial differences in bowling performance (ball speed and accuracy) between conditions and limited decline across the 6-over spell (Table 5.1). These findings are consistent with the minimal variation in ball speed or accuracy reported during 6 – 12-over spells in thermoneutral conditions (Burnett et al., 1995; Portus et al., 2000; Duffield et al., 2009a). Accordingly, despite the exacerbated physiological demands of medium-fast bowling in the heat (Devlin et al., 2001), increased thermoregulatory control after pre-cooling demonstrates little influence over motor control and subsequent skill-based bowling performance. Climatic conditions aside, medium-fast bowlers appear capable of maintaining ball speed and accuracy for the duration of a 6-over spell (~45 min). However, given the reduced physiological demand to achieve a similar bowling performance, the influence of pre-cooling on bowling skills across longer or repeated spells is of future interest.

Combined with the transfer of momentum and the summation of segmental velocities during the bowling action, optimal speed of the run-up leading into the delivery stride is important to generate ball speed (Glazier et al., 2000; Salter et al., 2007). Medium-fast bowlers must seek a balance between momentum and movement control at the point of ball release (Woolmer et al., 2008; Duffield et al., 2009a). Considering the paced and rhythmical nature of medium-fast bowling (Woolmer, et al., 2008), the lack of change in run-up speed with pre-cooling is not surprising (Figure 5.1). It is unlikely run-up speed would be increased by acute external interventions because of the risk of negative effects on technique and possible reductions in ball speed and accuracy. However, decreased muscle temperature arising from inappropriate cooling dosages or warm-up following cooling procedures could adversely affect voluntary force production and sprint performance (Skein et al., 2012), and so prevent optimal rhythm
Chapter 5 – Pre-Cooling for Medium-Fast Bowling

and momentum in the run-up. In context of the current data, a 10-min cricket specific warm-up after a 20-min pre-cooling strategy seems sufficient to avoid ergolytic effects on run-up characteristics, though practitioners are advised to trial such practices in training before implementing them in competition.

Unlike laboratory-based, self-paced intermittent-sprint protocols (Duffield & Marino, 2007; Minett et al., 2011), the largely standardised movement characteristics of the bowler’s run-up and matched activity patterns between overs reported here resulted in no change in sub-maximal distances covered (Table 5.2). However, maintenance of higher 20-m peak sprint speed between overs occurred with pre-cooling as the spell progressed. Similarly, Castle et al. (2006) demonstrated that pre-cooling preserved peak power output during repeated-sprint cycling efforts. Accordingly, reduced thermal demands after pre-cooling might override reductions in muscle recruitment and voluntary force production otherwise observed in hot conditions (Kay et al., 2001), thus allowing the maintenance of optimal (higher) self-selected exercise intensities (Kay et al., 1999; Duffield et al., 2010; Skein et al., 2012). Notably, while the bowling run-up involves a set distance at a consistent mean speed, the 20-m maximal sprint involved self-selected efforts that did not require sport-specific skill. Hence, the benefits of pre-cooling for medium-fast-bowling performance in the heat might not show in a single spell, though could maintain higher exercise intensity ‘off the ball’ during fielding activity, particularly over prolonged durations.

Pre-cooling strategies enhance thermoregulatory control through an increased heat-storage reserve as physiological responses to raised environmental and metabolic heat production are
reduced (Marino, 2002). The reduced thermal load before exercise (core temperature and skin temperature; Figure 5.2) and blunted core temperature response throughout the bowling spell could signify the combination of multiple cooling apparatus as an ecologically valid alternative to cold-water immersion for bowlers at risk of heat strain (Duffield et al., 2009d). Comparable transfer of physiological perturbations from laboratory-based interventions to the field (core temperature reduced ~0.2°C; Figure 5.2A) (Cotter et al., 2001; Castle et al., 2006; Minett et al., 2011) using practical techniques could allow repeated cooling exposures and prolonged protection against excessively raised core temperature responses in hot conditions. As a result, this artificial preservation of thermoregulatory control could reduce sweat responses and evaporative heat loss mechanisms and so alleviate cardiovascular strain as a larger centralised blood volume is maintained (Wendt et al., 2007).

The consistent and repetitive physical demands of medium-fast bowling explain comparable heart rate responses between conditions after each over (Figure 5.2C). However, lower heart rate values before each over with pre-cooling could indicate reduced sweat loss alterations in blood volume that preserve cardiac output and ease cardiovascular strain (Marino, 2002). Despite the brevity of a 6-over bowling spell in the context of a cricket innings, 1.7 – 2.1% reductions in nude body mass occurred, with inter-trial sweat rate discrepancies of ~400 mL representing a preservation of hydration status with pre-cooling. Given the difficulties of access and consumption of adequate fluid replacement for cricketers during competition in hot conditions (Gore et al., 1993), greater heat removal might reduce sweat responses and so buffer excessive involuntary dehydration. Consequently, maintenance of hydration status with pre-cooling might lessen thermoregulatory and cardiovascular symptoms of heat strain.
in medium-fast bowlers, to the benefit of health (Driscoll et al., 2008; Finch & Boufous, 2008) and skill-related outcomes (Devlin et al., 2001).

Despite the reduction in thermal strain of medium-fast bowlers after pre-cooling, few differences occurred between conditions for indirect biochemical markers of muscle damage, inflammation or stress (Table 5.3). Nevertheless, changes in creatine kinase during the bowling spell were reduced in pre-cooling trials. Similar to others, these data indicate that increased thermoregulatory demands are associated with greater creatine kinase release from muscle fibres (Alzeer et al., 1997) that is ameliorated with pre-cooling (Minett et al., 2011). However, given the sensitivity of cortisol to heat strain (Follenius et al., 1982) and the reduced thermal demands (physiological and perceptual) after pre-cooling, the lack of differences between conditions are unexpected, though not unknown (Hoffman et al., 1997). It is possible that a 6-over bowling spell is not long enough to evoke differences in biochemical stress responses between conditions and highlights a methodological limitation whereby peak concentrations are not be exhibited for several hours.

Finally, to complement a reduced physiological demand, perceptual strain (both rating of perceived exertion and thermal sensation) was largely suppressed throughout the bowling spell after pre-cooling (Figure 5.3). Lower subjective ratings of exertion and/or thermal sensation with pre-cooling are not novel, though often in free-paced activity these perceptual responses would be at least partially masked by higher intensities during intermittent-sprint exercise (Quod et al., 2006; Skein et al., 2012). This finding probably reflects the unique physical requirements of cricket fast-bowling. It could also support integrative afferent and
efferent feedback processes (lower physiological and perceptual demands) and explain higher 20-m sprint speeds as the bowling spell progressed (Tucker, 2009). Regardless, given the few differences in exercise performance and global positioning system unit data, pre-cooling in hot conditions eases subjective loads of the medium-fast bowler. Accordingly, while a 6-over spell represents only a portion of typical bowling demands, this apparent shielding of perceptual exertion after pre-cooling could provide ergogenic benefits as the duration of play is extended.

In conclusion, mixed-method whole-body pre-cooling had no effect on the skill-based performance of medium-fast bowlers in the heat. Although the brevity of a single 6-over spell might have contributed to the absence of conditional differences in skill performance, higher sprint speeds occurred during simulated fielding activity as the spell progressed. Further, the combination of multiple, practical cooling apparatus presents practitioners with an alternative to traditional immersion cooling techniques that improves physiological and perceptual states of medium-fast bowlers in hot conditions. Used strategically in the field, this mixed-method approach to pre-cooling could protect unacclimatised or at-risk players against environmental- and exercise-induced heat strain, blunting thermoregulatory demands and improve the quality of the session.
Cold-Water Immersion Decreases Cerebral Oxygenation but Improves Recovery After Intermittent-Sprint Exercise in the Heat

As published in the *Scandinavian Journal of Medicine & Science in Sports*
Abstract

This study examined the effects of post-exercise cooling on recovery of neuromuscular, physiological and cerebral haemodynamic responses following intermittent-sprint exercise in the heat. Nine participants underwent three post-exercise recovery trials including a control (CONT), mixed-method cooling (MIX) and cold-water immersion (10°C; CWI). Voluntary force and activation were assessed simultaneously with cerebral oxygenation (near-infrared spectroscopy) pre- and post-exercise, post-intervention, 1 h post- and 24 h post-exercise. Measures of heart rate, core temperature, skin temperature, muscle damage and inflammation were also collected. Both cooling interventions reduced heart rate, core and skin temperature post-intervention ($P < 0.05$). CWI hastened the recovery of voluntary force by $12.7 \pm 11.7\%$ (mean ± SD) and $16.3 \pm 10.5\%$ 1h post-exercise compared to MIX and CONT, respectively ($P < 0.01$). Voluntary force remained elevated $16.1 \pm 20.5\%$ 24h post-exercise after CWI compared to CONT ($P < 0.05$). Central activation was increased post-intervention and 1h post-exercise with CWI compared to CONT ($P < 0.05$), without differences between conditions 24 h post-exercise ($P > 0.05$). CWI reduced cerebral oxygenation compared to MIX and CONT post-intervention ($P < 0.01$). Further, cooling interventions reduced cortisol 1h post-exercise ($P < 0.01$), though only CWI blunted creatine kinase 24 h post-exercise compared to CONT ($P < 0.05$). Accordingly, improvements in neuromuscular recovery after post-exercise cooling appear disassociated with cerebral oxygenation; rather, reflecting reductions in thermoregulatory demands to sustain force production.
**Introduction**

Neuromuscular functioning and exercise capacity are inversely associated with an elevated core temperature (Tc), as the recruitment of motor units during voluntary activation of skeletal muscle is reduced under heat stress (Cheung, 2007). Concomitantly, increasing thermal strain reduces cerebral blood flow velocity and oxygenation (Nybo & Nielsen, 2001; González-Alonso et al., 2004), also contributing to declines in motor outflow and exercise performance (Rasmussen et al., 2010). Despite such findings, the recovery of cerebrovascular regulation in relation to voluntary force production after exercise- and environment-induced heat stress remains equivocal. Where repeated bouts of exercise in the heat are required, post-exercise cooling is demonstrated to alleviate high Tc and hasten the recovery of voluntary force, central activation (Pointon et al., 2012), and ensuing exercise performance (Vaile et al., 2008a; Peiffer et al., 2010). These findings may demonstrate post-exercise cooling to mitigate thermally-inhibited central nervous system (CNS) drive after hyperthermic exercise (Cheung, 2007). However, whether rapidly reducing the thermal strain developed during intermittent-sprint exercise in the heat might also ease cerebrovascular perturbations affecting corticomotor function is unknown.

González-Alonso et al. (2004) previously reported heat stress to reduce cerebral oxygenation during maximal exercise, as declines in middle cerebral artery blood flow velocity reflect a lowered mean arterial pressure (MAP) and cardiac output (Q). Such reductions in cerebral oxygenation are suggested to alter central motor output (Amman & Kayser, 2009), though it is yet to be determined whether these effects may be reversed with aggressive reduction of endogenous thermal strain. Indeed, hypoxic models indicate exercise capacity to return once oxygen delivery and uptake in the brain is restored (Nielsen et al., 1999). While
unsubstantiated under heat stress, it could be speculated that central blood volume shifts achieved via post-exercise cooling may regain cardiocirculatory homeostasis (Vaile et al., 2011), as greater MAP and Q increase cerebral perfusion, and presumably oxygenation, to improve compromised motor output to active musculature (Périard et al., 2012). This may be particularly prudent in hot conditions as declines in cerebral oxygenation that precipitate reduced exercise performance (Smith & Billaut, 2010) are likely exacerbated (González-Alonso et al., 2004; Rasmussen et al., 2010).

Therefore, the present study aimed to examine the effects of post-exercise cooling on physiological, neuromuscular, biochemical and perceptual measures of recovery following intermittent-sprint exercise in the heat. A further aim was to determine whether these interventions affected cerebral oxygenation and subsequent neuromuscular function. While the efficacy of cold-water immersion (CWI) in treating heat stress is unparalleled (Casa et al., 2007), we have previously shown a positive relationship between the magnitude of pre-cooling, voluntary force and intermittent-sprint performance in the heat (Minett et al., 2011). Given recent concerns surrounding the practical application of CWI in the field (Barwood et al., 2009), a dose response for post-exercise cooling was achieved via the use of: (1) whole-body CWI; and (2) mixed-method cooling (MIX) designed to maximise surface area coverage and maintain logistical practicality. We hypothesized that the larger dosage effects of CWI would improve the recovery of cerebral oxygenation and neuromuscular function compared to MIX and control (CONT), respectively.
Methods

Participants

Nine moderate- to well-trained, male team-sport athletes volunteered to participate in this study (mean ± standard deviation (SD): age 21 ± 2 y; stature 183.3 ± 7.0 cm; body mass 78.7 ± 8.1 kg). Participants were sub-elite, amateur level team-sport athletes and at the time of testing were undergoing in-season training, reporting ≥ 3 training sessions and competition on a weekly basis. Participants provided written and verbal informed consent and all experimental procedures were approved by the Ethics in Human Research Committee of the University.

Overview

Participants were familiarized with all equipment and procedures under experimental conditions before reporting to the laboratory for three separate experimental trials that were separated by 5 – 7 days. Each testing session included an intermittent-sprint exercise protocol (2 x 35 min bouts) completed on a 20 m tartan indoor running track in the heat. Environmental conditions were controlled using a customized gas heating system and four 2000 W electric heaters (Kambrook, Port Melbourne, Australia), with mean ± SD ambient temperatures maintained at 32.4 ± 1.0°C and 42.4 ± 6.1% relative humidity. Fluid intake was restricted to a standardized 350 mL of water ingested ad libitum throughout the exercise protocol, with complete consumption ensured during each trial. Upon completion, participants underwent a post-exercise recovery intervention administered using a randomized, repeated-measures crossover design. Physiological, neuromuscular and perceptual responses were obtained pre-, post-, 1 h post- and 24 h post-exercise. Dietary
intake and physical activity records were maintained 24 h pre-exercise and during the 24 h recovery period for the initial experimental trial and replicated thereafter. Participants abstained from strenuous activity and alcohol consumption 24 h pre- and caffeine and food substances 3 h pre-exercise.

**Exercise protocol**

After a standardized 5 min warm-up consisting of progressively increasing shuttle running speeds and 6 maximal sprint efforts, participants completed 2 x 35 min bouts (Bout 1 and 2) of intermittent-sprint exercise, interspersed by a 15 min mid-exercise passive recovery period. The exercise protocol was adapted from that reported in a companion paper as part of a series of investigations incorporating the movement patterns of cricket fast bowlers (Minett et al., 2011). In brief, each 35 min bout was identical, both involving five sets of 6 x 15 m sprints every 30 s as per a 6-ball cricket over. Sets of sprints were separated by 5 min periods of 15 m shuttles at intensities (hard run, jog and walk) instructed on a minute-by-minute basis. Participants returned to their starting positions at 50 s of each self-paced minute to commence the subsequent exercise intensity. Shuttle-run distances were recorded during the initial testing session and matched in the remaining trials to standardize individual workloads. Maximal 15 m sprint times were assessed with an infra-red timing system (Speedlight; Swift, Wacol, Australia), while sub-maximal shuttle distances were calculated using 1 m markings adjoining the running track. The reliability of sprint time variables in the present study demonstrate the Intraclass Correlation Coefficient (ICC) as $r= 0.50 – 0.70$ and Coefficient of Variation (CV) as $1.6 – 2.6\%$. Accordingly, participants completed 10 sets of sprints and eight periods of sub-maximal shuttle running, representing 2 x 5 over spells of fast bowling.
Cooling interventions

Participants underwent one of three 20 min recovery interventions (CWI, MIX or CONT) within 10 min of exercise completion. CWI involved submersion to the mesosternale in 10.0 ± 0.4°C cold water (Halson et al., 2008; Pointon et al., 2012). MIX was performed using a cold, wet towel positioned over the head, neck and shoulders, with an ice-vest covering the torso (Arctic Heat, Brisbane, Australia) and ice-packs applied to the hamstrings and quadriceps (Techni Ice, Frankston, Australia) (Minett et al., 2012). The towel was soaked in cold water (5.0 ± 0.5°C) and the ice-vest and ice-packs were stored at -20°C before application. Participants received no cooling during the CONT and sat passively in 32°C and 42% relative humidity throughout all treatments.

Measures

Neuromuscular function

Maximal voluntary contraction (MVC) and central activation of the right knee extensors were assessed pre- and post-exercise, post-intervention, 1 h post-exercise and 24 h post-exercise using a custom-built isometric dynamometer. Participants sat in an upright position (trunk-thigh angle of 100°) on a modified leg extension bench (York Barbell Co., Toronto, Canada), secured with an adjustable lap sash and padded ankle cuff superior to the lateral malleolus. A calibrated load cell (Model No. UU-K200; Dacell Co., Ltd., Cheongwon-gun, Chung-buk, Korea) was fixed between the moveable lever arm and the steel bench frame and connected to a BNC2100 terminal block and signal acquisition system (PXI1024; National Instruments, Austin, TX, USA). The MVC protocol involved 20 x 5 s isometric efforts completed using a work-to-rest ratio of 1:1. Force outputs were corrected for gravitation effects and torque
values quantified in relation to lever arm length during analyses using the methods of Cannon et al. (2008).

**Muscle activation**

Supramaximal stimulation of the femoral nerve was applied during contractions 1 – 4 and 17 – 20 of each MVC protocol. Reusable self-adhesive gel electrodes (90 x 50 mm; Verity Medical Ltd., Stockbridge, Hampshire, England) were positioned on the anterior thigh 3 cm below the inguinal fold and on the medio-posterior aspect of the upper thigh below the gluteal fold, serving as the cathode and anode respectively. The current applied to the femoral nerve was delivered by a Digitimer DS7 stimulator (Digitimer Ltd., Welwyn Garden City, Hertfordshire, England) using a single square-wave pulse with a width of 200 μs (400 V with a current of 100-450 mA) and customized LabVIEW software (version 8.0; National Instruments, North Ryde, Australia). Maximal peak twitch torque and M-wave amplitude were identified using incrementally increasing stimuli, and then increased by 10% to ensure supra-maximal stimulation. The central activation ratio (CAR) was calculated as the ratio between voluntary muscle torque and superimposed muscle torque as described by Kent-Braun and Le Blanc (1996).

**Surface electromyography (EMG)**

Knee extensor EMG was recorded during the MVC protocol, with differential surface electrodes (Bagnoli-16, Delsys Inc., Boston, MA, USA) positioned over the vastus medialis (VM) and vastus lateralis (VL) on the right thigh. EMG electrodes were positioned at the visual mid-point of the muscle belly and a self-adhesive reference electrode was attached to
the patella on the left leg. All placement sites were shaved, exfoliated and cleaned with an alcohol swab and electrodes and cables were taped to avoid any movement artifact. Further, a permanent marker was used to outline electrode placement to ensure consistency within and between testing sessions. Raw electrode output was pre-amplified and bandpass filtered, with a bandwidth frequency ranging from 20 to 450 Hz (common mode rejection ratio > 90dB; impedance input = 100MΩ; gain = 1000).

EMG amplitudes were determined via the root mean square (RMS) of the 300 ms following supramaximal stimulation and the MVC offset. Repolarisation of the superimposed M-wave and restoration of voluntary EMG signals were observed in all data sets by 300 ms post-stimulation, thus eliminating twitch artifact from contaminating the signal. Mean amplitude was quantified for both VM and VL; however, a mean value was expressed as an overall indication of neural drive to the knee extensors. EMG signals were normalized with respect to the RMS of M-wave amplitude and presented as percentage of the mean VM and VL M-wave amplitude. Processing of all neuromuscular data was performed using MATLAB software (R2010a; The MathWorks Inc., Natick, USA).

*Near-infrared spectroscopy (NIRS)*

A continuous-wave NIRS instrument (Oxymon MKIII, Artinis Medical Systems B.V., Zetten, The Netherlands) was used to examine changes in oxygenated ([O₂Hb]), deoxygenated ([HHb]), and total ([THb]) cerebral haemoglobin concentrations throughout the MVC protocols. The NIRS probe was placed over the left prefrontal lobe, between Fp1 and F3 (international EEG 10-20 system) (Perrey, 2008) and adjusted by < 5 mm to optimize
signal strength (Billaut et al., 2010). Optode placement sites were cleaned with an alcohol swab, marked with an indelible pen and then photographed to standardize positioning within and between sessions. Inter-optode distance was set at 3.5 cm using a black, plastic spacer and was affixed to the skin with double-sided self-adhesive disks. A black, elastic headband was worn over the probe to further secure placement and minimize the effects of ambient light. Changes in [O$_2$Hb] and [HHb] concentrations were calculated using a modified Beer-Lambert law based on the absorption coefficient of continuous wavelength infra-red light (856 and 764 nm) and age-dependant differential path-length factors (range: 5.76 – 5.85) (Duncan et al., 1996; Billaut et al., 2010). The [THb] was calculated as the sum of [O2Hb] and [HHb] to provide an indicative measure of regional blood volume (Van Beekvelt et al., 2001). In addition, the tissue saturation index (TSI; quantified as the ratio between [O2Hb] and [THb]), which reflects the dynamic balance between O$_2$ supply and O$_2$ consumption and is independent of near-infrared photon pathlength in tissue, was calculated as an additional index of tissue oxygenation (Boushel et al., 2001). NIRS data were recorded at 10 Hz and averaged over the last second of each isometric contraction throughout the MVC protocol. These data were then normalized against a 120 s baseline value collected before the commencement of each session while subjects sat quietly on the isometric dynamometer with their eyes closed. The reliability of baseline TSI in the present study demonstrate the ICC as r= 0.86 – 0.88 and CV as 1.8 – 2.0%.

**Venous blood collection and analyses**

The effects of cooling interventions on muscle damage, inflammation and anabolic/catabolic responses were quantified from venous blood samples collected pre-, post-, 1 h post- and 24 h post-exercise. Samples were drawn from an antecubital vein using an evacuated venipuncture
assembly and serum separator tubes (BD Vacutainer, North Ryde, Australia), allowed to clot at room temperature before centrifugation (4000 rpm for 10 min at 4°C) and serum storage at -20°C. Creatine kinase (CK) was determined using an enzymatic method and bichromatic rate technique (CV= 2.8%), while C-reactive protein (CRP) was quantified according to the particle enhanced turbidimetric immunoassay methods (CV= 6.2%; Dimension Xpand spectrophotometer, Dade Behring, Atlanta, USA). Testosterone and cortisol were assessed using a solid-phase, competitive chemiluminescent enzyme immunoassay (CV= 3.9% and 2.1% respectively; Immulite 2000, Diagnostic Products Corp., Los Angeles, USA). Data are presented as circulating concentrations and no corrections were made for alterations in plasma volume.

Physiological measures

Hydration status was assessed on arrival to the laboratory via the provision of a mid-stream urine sample to measure urine specific gravity (USG) (PAL-10S; Atago Co. Ltd., Tokyo, Japan) and changes in pre- and post-exercise body mass recorded using calibrated scales (HW150 K; A&D, Adelaide, Australia) as a measure of non-urinal fluid loss. Heart rate (HR) values were determined with a chest strap and wrist watch receiver (FS1; Polar Electro Oy, Kempele, Finland) and Tc was monitored through a telemetric capsule (VitalSense; Mini Mitter, Bend, USA) ingested 5 h pre-exercise. HR and Tc were recorded at 5 and 10 min intervals respectively during exercise, and every 5 min throughout the intervention period. The reliability (ICC= 0.99) and validity (r= 0.98) of Tc capsules have previously been reported as acceptable by Gant et al. (2006). Skin temperature (Tk) was measured at four sites (sternum, mid-forearm, mid-quadriceps and medial calf) pre- and post-exercise, post-intervention, 1 h post- and 24 h post-exercise using an infra-red thermometer (ThermoScan
3000; Braun, Kronberg, Germany) as per the methods of Burnham et al. (2006) (ICC= 0.96; r= 0.92). A weighted-mean Tsk was calculated using the Ramanathan (1964) formula and mean body temperature (T_b) was determined as described by Schmidt and Brück (1981).

**Perceptual measures**

Rating of perceived exertion (RPE; Borg CR-10 scale) was recorded every 5 min during the exercise protocol. Perceived thermal sensation (0= unbearably cold – 8= unbearably hot) was measured at 5 min intervals throughout exercise and intervention periods, whilst muscle soreness (0= normal – 10= extremely sore) was assessed pre-, post-, 1 h post- and 24 h post-session pre- and post-exercise, post-intervention, 1 h post- and 24 h post-exercise.

**Statistical analyses**

Data are presented as mean ± SD. A two-way (condition x time) repeated-measures analysis of variance (ANOVA) was performed to determine differences between cooling conditions (CWI vs. MIX vs. CONT). Unprotected pairwise comparisons (Protected Fisher’s LSD) were applied to determine the source of significance, which was accepted when P < 0.05. Analysis was performed using the Statistical Package for Social Sciences (SPSS v 17.0, Chicago, USA).
Chapter 6 – Post-Exercise Cooling for Recovery

Results

Intermittent-sprint exercise performance

Shuttle-run efforts were standardised between sessions to match individual workloads, with a mean total distance covered during the exercise protocol of 4159 ± 270 m. Specifically, 3496 ± 240 m, 833 ± 99 m and 449 ± 43 m were accumulated at hard running, jogging and walking intensities, respectively. Mean 15 m sprint times were not significantly different between conditions during the exercise protocol (CWI 2.73 ± 0.08 s vs. MIX 2.74 ± 0.07 s vs. CONT 2.76 ± 0.12 s; P= 0.30 – 0.63).

MVC and CAR

Mean MVC and CAR were significantly reduced pre- to post-exercise in all conditions (P= 0.001 – 0.05; Figure 6.1), without differences between conditions (P= 0.52 – 0.98). However, CWI hastened the return of neuromuscular function towards pre-exercise values, with higher mean MVC evident post-intervention, 1 h post-exercise and 24 h post-exercise compared to CONT (P= 0.002 – 0.05). Further, mean MVC was greater 1 h post-exercise after CWI compared with MIX (P= 0.006). While mean MVC was significantly lower than pre-exercise values for the duration of the 24 h recovery period in MIX and CONT conditions (P= 0.001 – 0.01), no differences were evident compared to pre-exercise measures 24 h post-exercise in CWI trials (P= 0.41). Moreover, CAR was significantly higher post-intervention and 1 h post-exercise in CWI trials compared to CONT (P= 0.007 – 0.03), and 1 h post-exercise compared to MIX (P= 0.01), respectively. No significant differences were observed in CAR between conditions 24 h post-exercise (P= 0.09 – 0.53), although CAR remained significantly lower than pre-exercise measures (P= 0.002).
**Voluntary EMG**

Mean RMS of VM and VL were higher post-intervention after CWI compared to CONT ($P=0.005$; Figure 6.1C). Further, CWI demonstrated a greater mean RMS of VM and VL 1 h post-exercise than MIX ($P=0.01$) and CONT ($P=0.003$), respectively. No differences were evident in the change in mean RMS of VM and VL in any condition over time ($P=0.13 – 1.00$).

**Potentiated M-wave properties**

M-wave amplitude was reduced pre- to post-exercise in all trials ($P=0.03 – 0.04$; Table 6.1). The exercise protocol demonstrated no significant effects on M-wave latency or duration ($P=0.07 – 0.91$). However, M-wave amplitude was significantly higher with CWI post-intervention compared to CONT ($P=0.01$). No significant differences were evident in any remaining M-wave variables ($P=0.08 – 0.98$).
Figure 6.1. A Mean ± SD peak torque, B central activation ratio, and C root mean square for combined mean vastus medialis and vastus lateralis for Cold-Water Immersion (CWI), Mixed-Method Cooling (MIX) and Control (CONT) trials.

*Significant difference between CWI and CONT ($P < 0.05$). ^Significant difference between CWI and MIX ($P < 0.05$).
Table 6.1. Mean ± SD potentiated M-wave properties of mean vastus medialis and vastus lateralis between Cold-Water Immersion (CWI), Mixed-Method Cooling (MIX) and Control (CONT) conditions and over time.

<table>
<thead>
<tr>
<th></th>
<th>Pre-Ex</th>
<th>Post-Ex</th>
<th>Post-Int</th>
<th>1 h Post-Ex</th>
<th>24 h Post-Ex</th>
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<tbody>
<tr>
<td><strong>Latency (ms)</strong></td>
<td></td>
<td></td>
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<tr>
<td>CONT</td>
<td>5.1 ± 1.5</td>
<td>6.1 ± 2.1</td>
<td>4.7 ± 1.9</td>
<td>5.3 ± 2.1</td>
<td>5.3 ± 1.7</td>
</tr>
<tr>
<td>MIX</td>
<td>5.2 ± 2.2</td>
<td>6.1 ± 1.9</td>
<td>5.1 ± 2.4</td>
<td>5.2 ± 1.8</td>
<td>5.5 ± 1.8</td>
</tr>
<tr>
<td>CWI</td>
<td>5.1 ± 2.2</td>
<td>6.2 ± 2.0</td>
<td>5.2 ± 2.3</td>
<td>5.1 ± 2.3</td>
<td>5.4 ± 2.3</td>
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<tr>
<td><strong>Duration (ms)</strong></td>
<td></td>
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<tr>
<td>CONT</td>
<td>7.1 ± 2.4</td>
<td>7.7 ± 2.2</td>
<td>7.6 ± 2.4</td>
<td>6.9 ± 2.5</td>
<td>7.6 ± 3.1</td>
</tr>
<tr>
<td>MIX</td>
<td>6.9 ± 2.6</td>
<td>7.8 ± 2.3</td>
<td>7.9 ± 2.7</td>
<td>6.8 ± 2.1</td>
<td>7.6 ± 2.4</td>
</tr>
<tr>
<td>CWI</td>
<td>7.2 ± 2.4</td>
<td>7.8 ± 2.3</td>
<td>9.7 ± 2.3</td>
<td>7.0 ± 1.9</td>
<td>7.5 ± 2.1</td>
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<tr>
<td><strong>Amplitude (mV)</strong></td>
<td></td>
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<tr>
<td>CONT</td>
<td>7.5 ± 2.1</td>
<td>5.7 ± 1.5^</td>
<td>5.8 ± 2.1</td>
<td>7.3 ± 2.2</td>
<td>7.6 ± 2.3</td>
</tr>
<tr>
<td>MIX</td>
<td>7.7 ± 2.2</td>
<td>5.5 ± 1.5^</td>
<td>7.3 ± 2.5</td>
<td>7.3 ± 1.5</td>
<td>7.4 ± 0.9</td>
</tr>
<tr>
<td>CWI</td>
<td>7.5 ± 1.9</td>
<td>5.7 ± 0.8^</td>
<td>8.6 ± 1.8*</td>
<td>7.8 ± 2.1</td>
<td>7.6 ± 1.7</td>
</tr>
</tbody>
</table>

* Significant difference compared to CONT condition (P < 0.05).  ^ Significant difference compared to pre-exercise (P < 0.05).
NIRS

Regional cerebral blood volume and oxygenation were significantly decreased in all trials pre- to post-exercise (↓ [O₂Hb], ↑ [HHb], ↓ [THb] and ↓ TSI; \( P= 0.001 – 0.05 \); Figure 6.2). An exacerbated reduction in [O₂Hb] was evident post-intervention in both CWI and MIX compared to CONT (\( P < 0.001 \)), albeit with greater reductions noted in CWI than MIX trials (\( P= 0.02 \)). CWI increased [HHb] (\( P= 0.04 \)) whilst lowering [THb] and TSI compared to CONT post-intervention (\( P= 0.001 – 0.01 \)). Despite a reduced [THb] after the MIX intervention (\( P= 0.001 \)), TSI remained unchanged compared to CONT (\( P= 0.99 \)), though was significantly higher than CWI (\( P= 0.01 \)). Nevertheless, suppressed [THb] indicates a reduced regional cerebral blood volume after CWI to be sustained 1 h post-exercise compared to remaining conditions (\( P= 0.03 \)). Similarly, [O₂Hb] and [HHb] were reduced with CWI compared to CONT (\( P= 0.04 – 0.05 \)); however, TSI was not significantly altered between conditions 1 h post-exercise (\( P= 0.08 – 0.91 \)). All variables had returned to pre-exercise values by 24 h post-exercise and no differences were present between conditions (\( P= 0.35 – 0.95 \)).
Figure 6.2. Changes in oxygenation of the prefrontal cortex between Cold-Water Immersion (CWI), Mixed-Method Cooling (MIX) and Control (CONT) conditions. A Mean ± SD [O₂Hb], B [HHb], C [THb], and D TSI.

* Significant difference between CWI and CONT ($P < 0.05$).  ^ Significant difference between CWI and MIX ($P < 0.05$).  + Significant difference between MIX and CONT ($P < 0.05$).
**Hydration, HR, T_c and T_sk**

No significant differences were observed in pre-exercise USG between conditions (CWI $1.015 \pm 0.006$ vs. MIX $1.015 \pm 0.008$ vs. CONT $1.014 \pm 0.007$; $P=0.66$ – 1.00). Nude body mass was significantly reduced pre- to post-exercise (CWI $1.86 \pm 0.33$ kg vs. MIX $1.82 \pm 0.33$ kg vs. CONT $1.83 \pm 0.25$ kg; $P<0.001$), with no differences between conditions ($P=0.60$ – 0.85). No significant differences were demonstrated in HR, $T_c$ and $T_sk$ between conditions during exercise ($P=0.09$ – 0.98; Figure 6.3). Increased HR and $T_c$ were evident pre- to post-exercise ($P<0.001$), despite no change in $T_sk$ over time in all conditions ($P=0.33$ – 0.79). Both CWI and MIX cooling significantly reduced $T_c$ during the intervention period compared to CONT ($P=0.001$ – 0.03), with a lower $T_c$ still evident 1 h post-exercise ($P=0.001$ – 0.009). Cooling reduced $T_sk$ post-intervention ($P<0.001$), with larger reductions apparent following CWI compared to MIX ($P<0.001$). However, this lowered $T_sk$ had dissipated by 1 h post-exercise with no differences observed between conditions ($P=0.41$ – 0.67). Both MIX and CWI reduced HR after 15 min and 20 min of post-exercise cooling compared to CONT ($P=0.03$ – 0.04).
Figure 6.3. A Mean ± SD heart rate, B core temperature, C skin temperature and D body temperature for Cold-Water Immersion (CWI), Mixed-Method Cooling (MIX) and Control (CONT) trials.

* Significant difference between CWI and CONT ($P < 0.05$). ^ Significant difference between CWI and MIX ($P < 0.05$). † Significant difference between MIX and CONT ($P < 0.05$).
Chapter 6 – Post-Exercise Cooling for Recovery

_Venous blood_

No significant differences were observed between conditions in pre- and post-exercise concentrations of CK, CRP, testosterone or cortisol ($P= 0.07 – 0.99$; Table 6.2). However, cortisol responses were lower 1 h post-exercise in both MIX ($P= 0.006$) and CWI conditions ($P= 0.003$) compared to CONT. CWI blunted CK 24 h post-exercise ($P= 0.047$). CRP and testosterone responses were not significantly affected in recovery following either cooling intervention ($P= 0.08 – 0.82$). CK was elevated at all time-points in each trial following intermittent-sprint exercise ($P= 0.001 – 0.01$), though this was not reflected in any change in CRP compared to pre-exercise values ($P= 0.07 – 0.92$). Testosterone increased over time in CONT trials ($P= 0.01 – 0.04$), with no time effects apparent for MIX or CWI conditions ($P= 0.08 – 0.99$). Finally, cortisol concentrations were higher compared to pre-exercise values at all time points in CONT ($P= 0.001 – 0.03$), post-exercise and 1 h post-intervention in MIX ($P= 0.003 – 0.02$), and post-exercise only in CWI trials ($P= 0.003$).
Table 6.2. Mean ± SD biochemical data comparison between Cold-Water Immersion (CWI), Mixed-Method Cooling (MIX) and Control (CONT) conditions.

<table>
<thead>
<tr>
<th></th>
<th>Pre-Ex</th>
<th>Post-Ex</th>
<th>1 h Post-Ex</th>
<th>24 h Post-Ex</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Creatine Kinase (UL⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONT</td>
<td>218 ± 147</td>
<td>451 ± 270^</td>
<td>465 ± 271^</td>
<td>741 ± 504^</td>
</tr>
<tr>
<td>MIX</td>
<td>268 ± 220</td>
<td>498 ± 358^</td>
<td>567 ± 383^</td>
<td>656 ± 585^</td>
</tr>
<tr>
<td>CWI</td>
<td>240 ± 90</td>
<td>463 ± 203^</td>
<td>495 ± 220^</td>
<td>513 ± 235*^</td>
</tr>
<tr>
<td><strong>C-Reactive Protein (mg L⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONT</td>
<td>1.41 ± 0.37</td>
<td>1.98 ± 1.42</td>
<td>1.89 ± 1.36</td>
<td>2.41 ± 1.44</td>
</tr>
<tr>
<td>MIX</td>
<td>1.49 ± 0.38</td>
<td>1.67 ± 0.34</td>
<td>1.71 ± 0.37</td>
<td>2.64 ± 1.94</td>
</tr>
<tr>
<td>CWI</td>
<td>1.63 ± 0.51</td>
<td>1.62 ± 0.36</td>
<td>1.79 ± 0.41</td>
<td>2.10 ± 0.93</td>
</tr>
<tr>
<td><strong>Testosterone (ng dL⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONT</td>
<td>314 ± 81</td>
<td>412 ± 114^</td>
<td>390 ± 113^</td>
<td>392 ± 138^</td>
</tr>
<tr>
<td>MIX</td>
<td>316 ± 102</td>
<td>361 ± 88</td>
<td>311 ± 71</td>
<td>316 ± 89</td>
</tr>
<tr>
<td>CWI</td>
<td>319 ± 71</td>
<td>347 ± 49</td>
<td>319 ± 67</td>
<td>347 ± 72</td>
</tr>
<tr>
<td><strong>Cortisol (nmol L⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONT</td>
<td>287 ± 109</td>
<td>500 ± 213^</td>
<td>658 ± 220^</td>
<td>419 ± 126^</td>
</tr>
<tr>
<td>MIX</td>
<td>262 ± 63</td>
<td>507 ± 184^</td>
<td>465 ± 241*^</td>
<td>317 ± 176</td>
</tr>
<tr>
<td>CWI</td>
<td>286 ± 78</td>
<td>500 ± 121^</td>
<td>348 ± 47*</td>
<td>279 ± 107</td>
</tr>
</tbody>
</table>

* Significant difference compared to CONT condition (P < 0.05). ^ Significant difference compared to pre-exercise (P < 0.05).
Perceptual

Mean RPE was not significantly different between conditions (CWI 5.9 ± 1.4 vs. MIX 6.0 ± 1.6 vs. CONT 6.3 ± 1.5; $P = 0.36 – 0.64$); nor were differences in RPE detected at any time-point throughout the exercise protocol ($P = 0.18 – 1.00$; Figure 6.4A). While thermal sensation was reduced during the intervention period with CWI and MIX compared to CONT ($P < 0.001$; Figure 6.4B), CWI remained lower than CONT 1 h post-exercise ($P = 0.03$). Perceived muscle soreness was increased after exercise ($P = 0.001 – 0.003$; Figure 6.4C), remaining elevated for the duration of the 24 h recovery period ($P = 0.001 – 0.007$). Further, CWI reduced perceived muscle soreness at all time points post-intervention compared to CONT ($P = 0.001$) and MIX 24 h post-exercise ($P = 0.02$). Lower muscle soreness was also reported with MIX compared to CONT 24 h post-exercise ($P = 0.01$).
**Figure 6.4.** A Mean ± SD rating of perceived exertion, B thermal sensation, and C muscle soreness between Cold-Water Immersion (CWI), Mixed-Method Cooling (MIX) and Control (CONT) conditions.

* Significant difference between CWI and CONT ($P < 0.05$). ^ Significant difference between CWI and MIX ($P < 0.05$). † Significant difference between MIX and CONT ($P < 0.05$).
Discussion

The present findings provide further insight into the benefits of CWI in improving acute recovery of neuromuscular contractile function after intermittent-sprint exercise in the heat. While both post-exercise cooling interventions reduced thermal strain (as evident via reductions in $T_c$, $T_s$, $T_b$, HR and thermal sensation), only CWI hastened the recovery of MVC, central activation and motor unit recruitment (RMS). Novel to this investigation, we report the effects of post-exercise cooling on cerebral haemodynamics, demonstrating reduced [O$_2$Hb] and [THb] after both CWI and MIX interventions. Importantly, greater deoxygenation of the prefrontal cortex apparent with a lower TSI after CWI appeared disassicated with subsequent improvement in neuromuscular function. Thus, enhanced recovery of MVC is more likely attributable to the faster return of central activation achieved via larger acute reduction in $T_c$ post-intervention or the decreased muscle soreness and blunted CK response evident at 24 h. Although MIX may assist physiological, thermoregulatory and perceptual recovery following exercise in hot conditions, the greater physiological perturbations achieved with CWI likely accelerated the recovery of disruptions to neuromuscular function as indicated by maintenance of contractile force that were not observed in MIX or CONT.

Post-exercise cooling techniques in hot conditions aim to rapidly reduce elevated thermoregulatory and cardiovascular strain, alleviating impaired neuromuscular function and facilitating the maintenance of subsequent exercise performance (Wilcock et al., 2006). That is, a return of voluntary force and activation has been shown upon reversal of high thermal strain after both passive heating/cooling (Morrison et al., 2004; Thomas et al., 2006) and exercise models (Pointon et al., 2012). The present findings indicate that intermittent-sprint
exercise in the heat leads to prolonged reductions in MVC torque and CAR (Figure 6.1). However, the greater reduction in $T_b$ over the duration of the post-exercise intervention (CWI $-2.18 \pm 0.36^\circ\text{C}\text{min}^{-1}$ vs. MIX $-1.14 \pm 0.42^\circ\text{C}\text{min}^{-1}$ vs. CONT $-0.31 \pm 0.15^\circ\text{C}\text{min}^{-1}$; $P < 0.001$) might reflect the faster rate of neuromuscular recovery and return of voluntary force. Considering the increased RMS values (Figure 6.1C), the ergogenic benefits of CWI may owe to greater central activation and subsequent gain in skeletal muscle recruitment (Pointon et al., 2012). These findings corroborate previously reported benefits of CWI on MVC recovery in temperate conditions (Bailey et al., 2007; Vaile et al., 2008b; Ingram et al., 2009; Peiffer et al., 2009); further, demonstrating the influence of cooling modes on the recovery of voluntary force, particularly given negligible improvements in MVC were noted in MIX trials. Consequently, the recovery of neuromuscular function could be speculated to be influenced by the magnitude of cooling administered (i.e. reductions in $T_c$, $T_{ak}$ and $T_b$; Figure 6.3), with the superior conductance properties and larger surface area coverage of CWI (Casa et al., 2007) likely to explain the performance outcomes.

Cooling-induced changes to circulatory characteristics, such as altered central blood volume or regional blood flow, are thought to protect post-exercise contractile function (Wilcock et al., 2006; Leeder et al., 2012); though it is unknown how these mechanisms operate, particularly in light of the observed improvements in voluntary activation and CNS drive (Pointon et al., 2011). A reasonable postulate is that reduced thermal load and increased centralized blood volume achieved with post-exercise cooling might increase cerebral oxygen availability and augment exercise capacity by maintaining neuronal activity (Rupp & Perrey, 2008; Billaut et al., 2010). However, we observed a post-intervention reduction in an index of cerebral blood volume ([THb]) in both cooling trials, though TSI was only reduced after CWI
Although decreased oxygenation of the prefrontal cortex has been linked with reduced voluntary force and power output during exercise in hypoxic conditions (Nybo & Rasmussen, 2007; Smith & Billaut, 2010), these detrimental effects to central drive may not always be replicated in hyperthermic conditions (Morrison et al., 2009). In fact, humans exhibit a large tolerance to changes in cerebral oxygenation in normoxic conditions, and are able to up-regulate neural drive (assessed via EMG measurements) and strenuous voluntary performance in the face of deoxygenation (Billaut et al., 2010). Underlying mechanisms to explain the divergent relationship between TSI and neuromuscular function observed here are speculative and require further investigation.

Traditionally, reduced thermal loads ($T_c$, and $T_{sk}$) and resultant peripheral vasoconstriction achieved using cold therapies have been suggested to increase central blood volume, and through an increased MAP and Q, enhance muscle blood flow to maintain performance during repeated exercise bouts (Vaile et al., 2008a). Provided the larger centralized blood volume achieved with CWI as suggested in the present study and elsewhere (Peiffer et al., 2009; Gregson et al., 2011; Vaile et al., 2011), it is noteworthy that no differences in HR were observed post-intervention between cooling trials (i.e. CWI vs. MIX) (Figure 6.3A). Given the improvements in MVC torque, CAR and RMS apparent only after CWI, these data may suggest the absence of cardiodynamic contributions to neuromuscular recovery after intermittent-sprint exercise in the heat. Interestingly, these events seemingly differ to the findings of Périard et al. (2012) who linked declining cerebral oxygenation with higher HR during hyperthermic exercise. Intuitively then, narrowing the $T_c – T_{sk}$ gradient via post-exercise cooling should reduce peripheral blood flow required for heat loss, increasing MAP and Q (↓ HR), and so cerebral perfusion, highlighted to influence aerobic performance under
heat stress (Cheuvront et al., 2010). Regardless, our data indicates moderate reductions in cerebral oxygenation after post-exercise cooling in the heat as unconstraining of CNS drive, perhaps indicating the magnitude of cooling-induced reductions in $T_c$ and $T_{sk}$ as mediators of neuromuscular recovery and not lowered cerebral perfusion as related to cardiovascular strain.

Regardless of the centrally-mediated mechanisms discussed above, an alternative proposition pertaining to the benefits of post-exercise cooling relates to the blunted inflammatory responses often observed with such recovery techniques (Gregson et al., 2011). Interstitial protein and muscle enzyme release in addition to hormonal profiles may characterize exercise-induced muscle damage, inflammation and stress, indirectly highlighting the functional status of skeletal muscle (Halson et al., 2008; Pournot et al., 2011). Corroborating previous reports (Ingram et al., 2009; Pournot et al., 2011), CK efflux was attenuated with CWI 24 h post-exercise (Table 6.2). Despite this, post-exercise cooling demonstrated no effect on CRP at any time-point, though lower cortisol might reflect an ameliorated anti-inflammatory response 1 h post-exercise in MIX and CWI trials. Cooling-induced vasoconstriction is suggested to aid the maintenance of cellular integrity by decreasing circulatory and lymphatic permeability, easing interstitial fluid gain and blunting inflammatory events following exercise-induced muscle damage (Wilcock et al., 2006). Thus, while the efficacy of post-exercise cooling in improving biochemical perturbations incurred during exercise is contentious (Leeder et al., 2012), the maintenance of MVC torque in the CWI trial 24 h post-exercise, irrespective of similar CAR and RMS, may reflect sustained skeletal muscle structure, and so improved peripheral contractile force.
Further to the observed reduction in physiological strain, the present findings also highlight lowered subjective perceptions of soreness following post-exercise cooling (Figure 4). The analgesic effects of cooling are well documented (Leeder et al., 2012), potentially easing ratings of muscle soreness by mitigating acute tissue oedema and ensuing inflammatory responses to muscle damage (Bailey et al., 2007; Vaile et al., 2008b). Interestingly, CWI lowered reported muscle soreness at both acute (post-intervention and 1 h post-exercise) and delayed-onset time points (24 h post-exercise), though only 24 h post-exercise in the MIX trial. Considering the minimal changes observed in inflammatory markers (CRP) and the absence of any measurement of swelling, potential placebo effects of post-exercise cooling cannot be discounted (Leeder et al., 2012). However, when coupled with the greater reductions in thermal strain (T_c, T_d, and thermal sensation) and the hydrostatic pressure associated with CWI (Wilcock et al., 2006), differences in muscle soreness between recovery methods might reflect the greater magnitude of cooling stimulus incurred. Still, if and/or how improved perceptual ratings of muscle soreness may influence subsequent neuromuscular performance is yet to be identified.

Finally, although these findings add novel insight into the effects of post-exercise cooling and neuromuscular recovery under heat stress, it is prudent that several limitations are acknowledged. Hyperthermic exercise reportedly reduces cerebral oxygenation (Nybo & Nielsen, 2001; Rasmussen et al., 2010; Périard et al., 2012) and is proposed as a contributing modulator of central fatigue (Nybo & Rasmussen, 2007). Our premise was that the removal of high thermal loads following exercise in the heat might alleviate these cerebrovascular perturbations and so hasten the recovery of CNS drive. Inherently, this implies the improvement of cerebral blood flow characteristics otherwise compromised with
hyperthermia (Nybo & Nielsen, 2001). The NIRS technique utilised here provides a non-invasive measure of cerebrovascular function, though underestimates cerebral blood flow values in comparison with direct (e.g. transcranial doppler) or anatomical measures (e.g. positron emission tomography) (Perrey, 2008). For this reason, we have presented changes in cerebral oxygenation in relation to baseline measures. Nevertheless, despite the high reliability of baseline values reported here, the absence of any direct blood flow assessment remains a limitation and warrants further inquiry. Future study would benefit from examining cerebrovascular and metabolic activity in the brain during recovery following post-exercise cooling in the heat as an index of neuronal activation.

In summary, these findings highlighted the physiological, cerebral haemodynamic and perceptual effects of post-exercise cooling and subsequent influence on neuromuscular recovery following intermittent-sprint exercise in the heat. Importantly, CWI hastened the recovery of voluntary force, increasing central activation and easing thermal strain. A novel finding is the reduction in cerebral oxygenation and improved CNS drive after CWI, suggesting the blood volume shift to be a reflex response to greater heat removal with post-exercise cooling. Thus, these changes in cerebral haemodynamics after post-exercise cooling do not appear to present a regulatory pathway for the recovery of MVC and CAR. Instead, corresponding differences in cooling magnitude between conditions (CWI > MIX > CONT) point to thermoregulatory and cardio-circulatory perturbations incurred during post-exercise cooling as reflective of the physiological and perceptual recovery achieved.
Effects of Mixed-Method Cooling on Recovery of Medium-Fast Bowling Performance in Hot Conditions on Consecutive Days

As published in the Journal of Sports Sciences
Abstract

This investigation examined physiological and performance effects of cooling on recovery of medium-fast bowlers in the heat. Eight medium-fast bowlers completed two randomised trials, involving two sessions completed on consecutive days (Session 1: 10-overs and Session 2: 4-overs) in 31 ± 3°C and 55 ± 17% relative humidity. Recovery interventions were administered for 20 min (mixed-method cooling vs. control) after Session 1. Measures included bowling performance (ball speed, accuracy, run-up speeds), physical demands (global positioning system, counter-movement jump), physiological (heart rate, core temperature, skin temperature, sweat loss), biochemical (creatine kinase, C-reactive protein) and perceptual variables (perceived exertion, thermal sensation, muscle soreness). Mean ball speed was higher after cooling in Session 2 (118.9 ± 8.1 vs. 115.5 ± 8.6 km h⁻¹; P= 0.001; d= 0.67), reducing declines in ball speed between sessions (0.24 vs. -3.18 km h⁻¹; P= 0.03; d= 1.80). Large effects indicated higher accuracy in Session 2 after cooling (46.0 ± 11.2 vs. 39.4 ± 8.6 AU; P= 0.13; d= 0.93) without affecting total run-up speed (19.0 ± 3.1 vs. 19.0 ± 2.5 km h⁻¹; P= 0.97; d= 0.01). Cooling reduced core temperature, skin temperature and thermal sensation throughout the intervention (P= 0.001-0.05; d= 1.31-5.78) and attenuated creatine kinase (P= 0.04; d= 0.56) and muscle soreness at 24 h (P= 0.03; d= 2.05). Accordingly, mixed-method cooling can reduce thermal strain after a 10-over spell, improve markers of muscular damage and discomfort alongside maintained medium-fast bowling performance on consecutive days in hot conditions.
Chapter 7 – Cooling for Recovery of Medium-Fast Bowlers

Introduction

Training and competition demands of medium-fast bowlers are often characterised by multiple and prolonged spells on consecutive days (Orchard et al., 2009). Individual spells evoke pronounced physiological responses (Duffield et al., 2009a), reflective of the mechanical strain and eccentric loading (Bartlett et al., 1996; Noakes & Durandt, 2000) associated with repeated high-intensity intermittent-bouts (Petersen et al., 2010b). Competition scheduling in hot and humid conditions can also be unfavourable for bowling performance (Devlin et al., 2001), as physical demands are compounded by impaired heat loss mechanisms and increased heat strain (Gore et al., 1993; Noakes & Durandt, 2000). Cooling after exercise in the heat can reduce physiological and perceptual demands and improve subsequent exercise performance (Barwood et al., 2009; Vaile et al., 2008a). Accordingly, medium-fast bowlers could benefit from recovery strategies after training and/or competition to alleviate thermal strain and optimise readiness for ensuing spells over consecutive sessions or days.

Recovery strategies involving cold-therapy techniques are common in team sports (Montgomery et al., 2008; Rowsell et al., 2009). In particular, cold-water immersion after exercise can alleviate physiological demands associated with heat strain, oedema, soreness and reduced contractile function (Wilcock et al., 2006; Vaile et al., 2008a; Peiffer et al., 2010). The underlying mechanisms of the ergogenic effects of cold therapy on exercise performance are equivocal, although they could reduce cardiovascular and thermal strain, inflammation, muscle damage responses and perceptual discomfort (Wilcock et al., 2006). Until recently, few studies have examined effects of cooling interventions on recovery from exercise performed over consecutive days (Montgomery et al., 2008; King & Duffield, 2009;
Rowsell et al., 2009); moreover, effects on sport-specific skill performance are unknown. Despite the high thermal conductivity of cold-water immersion providing an effective cooling technique (Hadad et al., 2004), logistical and environmental restrictions prevent widespread implementation in the field (Barwood et al., 2009). Accordingly, the combined use of multiple practical and portable cooling techniques (for example, ice-vests, ice-packs, and cool towels) could offer alternatives to cold-water immersion and warrants investigation. Given an appropriate dosage of cold therapy is administered (Ranalli et al., 2010), mixed-method cooling could provide medium-fast bowlers with a practical recovery method wherever access to whole-body immersion techniques are not available.

Sustained medium-fast bowling performance requires players repeatedly to accommodate physiological demands, often under climatic conditions of high thermal stress and with brief periods of recovery (Noakes & Durandt, 2000; Petersen et al., 2010b). Accordingly, cold therapy could be a suitable post-exercise intervention for medium-fast bowlers to reduce physiological and perceptual strain, and restore exercise performance (Wilcock et al., 2006). No previous research has reported the effectiveness of mixed-method cooling on recovery of exercise performance over consecutive days or the effect of cooling after exercise on ensuing medium-fast bowling performance. Thus, the aim of the present study was to investigate physiological, perceptual and performance effects of mixed-method cooling on recovery after a 10-over medium-fast bowling spell in the heat.
Chapter 7 – Cooling for Recovery of Medium-Fast Bowlers

Methods

Participants

Eight, male medium-fast bowlers (mean ± standard deviation: age 23.3 ± 4.9 y; stature 187.8 ± 5.9 cm; body mass 83.3 ± 7.3 kg; sum of seven skinfolds 67.8 ± 24.9 mm; Yo-Yo intermittent recovery test level 18.1 ± 0.7) volunteered for this study. Participants were members of an Australian state squad, and completed training and competition six days a week. From these eight participants, six were full-time professional cricketers, with four having experienced age-group (Australia U’19’s) or full international competition. Approval for the study was provided by the Ethics in Human Research Committee of the University.

Overview

Using a randomised, repeated-measures cross-over design, participants completed two trials, with each condition (mixed-method cooling vs. control) involving two standardised testing sessions on consecutive days. Immediately after a 10-over bowling spell (Session 1), participants undertook a 20-min recovery intervention and returned 24 h later to complete an additional 4-over bowling spell (Session 2). All bowling was standardised according to a modified version of the Cricket Australia-Australian Institute of Sport fast-bowling skills test (Portus et al., 2010) conducted in environmental conditions of 30.4 ± 3.8°C, 55.7 ± 13.6% relative humidity and 31.2 ± 1.9°C, 53.6 ± 23.8% relative humidity for Sessions 1 and 2, respectively. Participants refrained from strenuous exercise and alcohol 24 h before, and all caffeine and food substances 3 h before each testing session. Self-reported physical activity and dietary records were completed for the 24 h before exercise for the initial trial and
replicated thereafter. Data collection was completed in-season and trials were separated by at least seven days.

**Exercise protocol**

Participants completed a standardised 10-min warm-up (jogging, stretching and practice deliveries) as completed in match conditions. Subsequently, a 10-over bowling spell (60 balls) was completed using a new 156-g four-piece cricket ball (Club Match, Kookaburra, Melbourne, Australia) in an outdoor turf-net facility. The bowling spells incorporated an adaptation of the Cricket Australia-Australian Institute of Sport fast-bowling skills test, whereby participants completed a randomised assortment of short-, good-, and full-length deliveries on off-stump and leg-stump lines at match intensities. The successful execution of each delivery was assessed via observation according to its relative proximity to corresponding 20 x 20-cm grids highlighted on a vertical target on the popping crease at the batsman’s end. Bowling in pairs and alternating overs, participants completed physical activities between overs to simulate fielding activities as previously reported (Duffield et al., 2009a; Minett et al., 2012). Specifically, these activities included the completion of a 10-m walk on each delivery and a 20-m sprint on the 2\textsuperscript{nd} and 4\textsuperscript{th} ball of each over. A standardised 600 mL of water was consumed throughout the bowling spell and all procedures were repeated for the 4-over bowling spell (24 balls) the following day. Bowling spells were limited in Session 2 to simulate the scheduling of One day and Twenty20 matches on consecutive days that is encountered in professional cricket.
Cooling intervention

Recovery treatments were administered 10 min after completion of the 10-over bowling spell (Session 1) and maintained for 20 min while participants rested passively in a seated position. Cooling was performed using a mixed-method technique, whereby a towel soaked in cold water \((5.0 \pm 0.5°C)\) was worn over the head, neck and shoulders, an ice-vest covered the torso (Arctic Heat, Brisbane, Australia) and ice-packs were applied to the quadriceps and hamstrings (Techni Ice, Frankston, Australia). The ice-vest and ice-packs were frozen at \(-20°C\) before application. This cooling strategy was selected as an alternative to cold-water immersion and was designed to minimise environmental (water access) and logistical constraints (cooling a full team), improve portability and reduce reliance on inadequate facilities when travelling (Duffield et al., 2009d). Participants received no cooling stimulus and sat passively for 20 min in change room conditions during control trials.

Performance measures

All deliveries were monitored for ball speed and accuracy during each bowling spell. Ball speed was determined using a cordless radar gun (R1010, JUGS Sports, Tualatin, USA) positioned approximately 5 m behind the bowler’s arm and aimed to determine ball speed at the point of release. Bowling accuracy was assessed according to a numerical value (0-100 arbitrary units [AU]) scaled relative to the participant’s ability to hit tester-instructed grid-based targets as per the Cricket Australia-Australian Institute of Sport fast-bowling skills test (Portus et al., 2010). Total run-up and final 5-m run-up speeds were recorded with a wireless infra-red timing system (Brower Timing Systems, Draper, USA).
Participants wore a 5-Hz global positioning system device (SPIelite, GPSports, Canberra, Australia) harnessed between the superior sections of the scapular to record distance and speed throughout the bowling spells. Global-positioning-system data were analysed at the conclusion of each session using Team AMS software (Version 2.1, GPSports, Canberra, Australia) and categorised as low-intensity activity (< 7.0 km h\(^{-1}\)), moderate-intensity activity (7.0 – 14.4 km h\(^{-1}\)), high-intensity activity (> 14.5 km h\(^{-1}\)) and very-high intensity activity (> 20 km h\(^{-1}\)) (Duffield et al., 2009a; Rampinini et al., 2007).

Counter-movement jump height was assessed from time in flight using an Optojump photocell system (Microgate, Bolzano, Italy) before and after Session 1, 1 h after Session 1, and before and after Session 2. From an upright position, participants were instructed to place their hands on their hips to eliminate arm swing and complete 10 maximal counter-movement jump efforts. No instruction was provided with regards to counter-movement depth or contraction speed. This method is reported as a valid (intra-class correlation coefficient= 0.998) and reliable (intra-class correlation coefficient= 0.989; coefficient of variation= 2.2%) measure of counter-movement jump height (Glatthorn et al., 2011).

**Physiological measures**

Participants ingested a telemetric core-temperature capsule (VitalSense, Mini Mitter, Bend, USA) approximately 5 h before Session 1 to ensure passage into the gastrointestinal tract. A mid-stream urine sample was collected on arrival for the determination of urine specific gravity (PAL-10S, Atago Co. Ltd., Tokyo, Japan) and nude body mass was determined before and after each session to the nearest 0.05 kg using electronic scales (WW114A, Conair
Corp., Stamford, USA) to estimate sweat loss. Participants were fitted with a heart rate monitor (RS400, Polar Electro Oy, Kempele, Finland) and skin sites marked at the sternum, mid-forearm, mid-quadriceps and medial calf for determination of temperature with an infra-red thermometer (ThermoScan 3000, Braun, Kronberg, Germany) (Burnham et al., 2006). Heart rate and core temperature responses were recorded before and after each over and at 10 min intervals throughout the recovery protocol. The skin temperature measures were assessed before, during and after the bowling spell, every 10 min during the intervention period and 1 h after the end of Session 1 and before and after Session 2. The weighted-mean skin temperature values were calculated as per Ramanathan (1964).

Given the high physical demands of medium-fast bowling, blood samples were drawn from a superficial forearm vein before, after and 24 h after Session 1 to determine time-course changes in creatine kinase, and C-reactive protein, as indirect indicators of muscle damage and inflammation. All samples were drawn directly into serum separator tubes (BD Vacutainer, North Ryde, Australia) using standard venipuncture techniques and centrifuged at 4000 rpm for 10 min. To avoid inter-assay variation, the serum was stored at -20°C and analysed in a single run once all specimens had been collected. Biochemical profiles were obtained according to the manufacturer’s instructions (Siemens Healthcare Diagnostics Inc., Newark, USA) and intra-assay coefficients of variation ranged from 0.8 – 5.2%.
**Perceptual measures**

Ratings of perceived exertion (Borg CR-10 scale) were recorded after each over. Subjective ratings of thermal stress (0= unbearably cold – 8= unbearably hot) were assessed throughout the bowling spell (before, during, and after), every 10 min during the recovery intervention and 1 h after the initial bowling spell. Further, perceived muscle soreness (0= normal – 10= extremely sore) was assessed before, after, 1 h after and 24 h after the 10 over bowling spell.

**Statistical Analysis**

Data are reported as mean ± standard deviation. A within groups factorial ANOVA was used to compare groups by time. Confidence interval adjustments were completed with a Fisher’s least significant difference. Significance was accepted where $P < 0.05$. Results were analysed with the Statistical Package for Social Sciences (SPSS v 17.0, Chicago, USA). The magnitudes of differences are expressed as standardised effect sizes (Cohen’s $d$; Cohen, 1988). Effect sizes of $< 0.20$ are classified as ‘trivial’, $0.20 – 0.49$ as ‘small’, $0.50 – 0.79$ as ‘moderate’, and $> 0.80$ as ‘large’ effects.
Results

Performance

Mean ball speed (cooling 118.7 ± 7.9 km h\(^{-1}\) vs. control 118.0 ± 8.0 km h\(^{-1}\); \(P= 0.47; d= 0.12\)) and peak ball speed (cooling 125.8 ± 6.6 km h\(^{-1}\) vs. control 125.0 ± 7.0 km h\(^{-1}\); \(P= 0.29; d= 0.16\)) did not differ between conditions during Session 1. Further, mean ball speeds did not differ between conditions in Session 1 during each individual over (Figure 7.1A; \(P= 0.07 – 0.57; d= 0.01 – 0.37\)); though peak ball speeds were greater at Over 1 (Figure 7.1B; \(P= 0.01; d= 0.44\)) and Over 7 (\(P= 0.03; d= 0.34\)) during cooling trials. Mean ball speed (cooling 118.9 ± 8.1 km h\(^{-1}\) vs. control 115.5 ± 8.6 km h\(^{-1}\); \(P= 0.001; d= 0.67\)) and peak ball speed (cooling 124.9 ± 9.1 km h\(^{-1}\) vs. control 120.6 ± 9.1 km h\(^{-1}\); \(P= 0.004; d= 0.76\)) were greater in Session 2 during cooling trials. Further, there was a large effect size for cooling to maintain mean ball speed between conditions (cooling 0.24 ± 2.50 km h\(^{-1}\) vs. control -3.18 ± 2.86 km h\(^{-1}\); \(P= 0.26; d= 1.07\)). Specifically, mean ball speeds were greater during each over in Session 2 in the cooling condition (\(P= 0.001 – 0.01; d= 0.53 – 0.77\)), with peak ball speed greater at Over 1 (\(P= 0.04; d= 0.64\)), Over 2 (\(P= 0.01; d= 0.73\)) and Over 4 (\(P= 0.001; d= 1.05\)). There were no differences between conditions in mean bowling accuracy in Session 1 (cooling 48.0 ± 9.7 AU vs. control 46.6 ± 5.9 AU; \(P= 0.61; d= 0.24\)); though large effect sizes indicated that mean bowling accuracy was greater at Over 6 (\(P= 0.28; d= 0.86\)) and Over 8 (\(P= 0.15; d= 0.99\)) but less at Over 10 (\(P= 0.06; d= 0.93\)) in cooling trials. Importantly, a large effect size indicated higher mean bowling accuracy in the cooling trial during Session 2 (cooling 46.0 ± 11.2 AU vs. control 39.4 ± 8.6 AU; \(P= 0.13; d= 0.93\)), most notably in Over 1 (\(P= 0.25; d= 0.90\)). Further, a large effect size indicated a greater maintenance of mean bowling accuracy between sessions in the cooling condition (cooling -1.98 ± 6.39 AU vs. control -7.23 ± 7.42 AU; \(P= 0.26; d= 1.07\)).
Figure 7.1. Mean ± standard deviation ball speed, peak ball speed and bowling accuracy per over during repeated bowling spells on consecutive days.
There were no differences and only trivial-to-moderate effect sizes for mean run-up speed (cooling $19.1 \pm 2.4 \text{ km h}^{-1}$ vs. control $20.3 \pm 3.6 \text{ km h}^{-1}$; $P = 0.45$; $d = 0.55$) and mean final 5 m run-up speed (cooling $20.8 \pm 1.3 \text{ km h}^{-1}$ vs. control $20.9 \pm 1.8 \text{ km h}^{-1}$; $P = 1.00$; $d = 0.03$) between conditions during Session 1 (Figure 7.2). Similarly, mean run-up speed (cooling $19.0 \pm 3.1 \text{ km h}^{-1}$ vs. control $19.0 \pm 2.5 \text{ km h}^{-1}$; $P = 0.97$; $d = 0.01$) and mean final 5 m run-up speed (cooling $20.0 \pm 1.6 \text{ km h}^{-1}$ vs. control $19.6 \pm 1.5 \text{ km h}^{-1}$; $P = 0.19$; $d = 0.38$) did not differ between conditions in Session 2. Mean run-up speed within-conditions did not differ between sessions ($P = 0.14 – 0.97$; $d = 0.05 – 0.58$); although, mean final 5-m run-up speeds were largely reduced from Session 1 to Session 2 in control trials ($P = 0.04$; $d = 1.05$), but only moderately reduced in the cooling condition ($P = 0.19$; $d = 0.77$).

The time-motion demands of Session 1 and Session 2 are presented in Table 7.1. There were no differences and trivial-to-moderate effect sizes between conditions for any mean total or categorised distances covered ($P = 0.11 – 1.00$; $d = 0.03 – 0.39$). However, mean peak 20-m sprint speeds between overs were greater in cooling trials after Over 2 ($P = 0.04$; $d = 1.03$), Over 3 ($P = 0.003$; $d = 1.00$) and Over 4 ($P = 0.02$; $d = 1.43$) in Session 2. Mean countermovement jump height did not differ between conditions at any time point in either Session 1 or 2 (Figure 7.3; $P = 0.25 – 0.88$; $d = 0.03 – 0.30$). Nevertheless, cooling reduced countermovement jump height 1 h after the bowling spell over resting values ($P = 0.02$; $d = 1.08$).
Figure 7.2. Overall total run-up and final 5 m run-up speeds for each ball of a repeated bowling spells on consecutive days.
Table 7.1. Mean ± standard deviation time-motion analysis of selected movement patterns, distances covered and peak sprint speed achieved between overs during medium-fast bowling spells on consecutive days.

<table>
<thead>
<tr>
<th></th>
<th>Session 1 Control</th>
<th>Session 1 Cooling</th>
<th>Session 2 Control</th>
<th>Session 2 Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8676 ± 1295</td>
<td>8684 ± 1061</td>
<td>3462 ± 645</td>
<td>3424 ± 521</td>
</tr>
<tr>
<td>Very-high-intensity activity</td>
<td>738 ± 550</td>
<td>704 ± 503</td>
<td>264 ± 211</td>
<td>282 ± 199</td>
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<tr>
<td>High-intensity activity</td>
<td>1656 ± 427</td>
<td>1658 ± 314</td>
<td>650 ± 166</td>
<td>647 ± 144</td>
</tr>
<tr>
<td>Moderate-intensity activity</td>
<td>1019 ± 379</td>
<td>951 ± 106</td>
<td>373 ± 54</td>
<td>371 ± 37</td>
</tr>
<tr>
<td>Low-intensity activity</td>
<td>5263 ± 649</td>
<td>5371 ± 332</td>
<td>2175 ± 343</td>
<td>2125 ± 191</td>
</tr>
<tr>
<td>Speed (m s(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very-high-intensity activity</td>
<td>5.80 ± 0.89</td>
<td>5.83 ± 0.25</td>
<td>5.51 ± 0.27</td>
<td>5.75 ± 0.29</td>
</tr>
<tr>
<td>High-intensity activity</td>
<td>5.28 ± 0.60</td>
<td>5.40 ± 0.38</td>
<td>5.10 ± 0.33</td>
<td>5.25 ± 0.28</td>
</tr>
<tr>
<td>Moderate-intensity activity</td>
<td>3.03 ± 0.16</td>
<td>3.02 ± 0.10</td>
<td>3.03 ± 0.28</td>
<td>3.03 ± 0.11</td>
</tr>
<tr>
<td>Low-intensity activity</td>
<td>1.02 ± 0.13</td>
<td>1.01 ± 0.08</td>
<td>1.05 ± 0.11</td>
<td>1.12 ± 0.23</td>
</tr>
<tr>
<td>Peak sprint speed (km h(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 1</td>
<td>21.7 ± 2.5</td>
<td>21.6 ± 2.7</td>
<td>21.0 ± 1.9</td>
<td>21.6 ± 2.8</td>
</tr>
<tr>
<td>Over 2</td>
<td>21.8 ± 3.2</td>
<td>21.8 ± 3.2</td>
<td>20.1 ± 2.1</td>
<td>21.6 ± 2.1(^*)</td>
</tr>
<tr>
<td>Over 3</td>
<td>21.5 ± 3.6</td>
<td>22.0 ± 3.2</td>
<td>20.3 ± 2.6</td>
<td>22.2 ± 2.3(^*)</td>
</tr>
<tr>
<td>Over 4</td>
<td>22.0 ± 3.1</td>
<td>22.4 ± 2.3</td>
<td>19.9 ± 2.2</td>
<td>22.1 ± 1.7(^*)</td>
</tr>
<tr>
<td>Over 5</td>
<td>21.2 ± 3.9</td>
<td>22.4 ± 2.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 6</td>
<td>21.0 ± 3.3</td>
<td>21.6 ± 2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 7</td>
<td>21.5 ± 3.1</td>
<td>22.4 ± 3.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 8</td>
<td>21.3 ± 3.7</td>
<td>22.3 ± 3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 9</td>
<td>21.9 ± 3.6</td>
<td>22.6 ± 4.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 10</td>
<td>22.4 ± 4.2</td>
<td>22.5 ± 3.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant difference between conditions \(P < 0.05\). \(^*\) Large effect size between conditions \(d > 0.80\).
**Figure 7.3.** Mean ± standard deviation counter-movement jump height between Cooling and Control conditions.

* Significant difference compared to pre values ($P < 0.05$).
Physiological

While there were no differences in mean heart rate response between conditions during either bowling Session (Figure 7.4A; $P= 0.40 – 0.97$; $d= 0.01 – 0.53$), Session 1 values were greater than those recorded in Session 2 across both trials ($P= 0.002 – 0.04$; $d= 0.81 – 1.28$). There were no differences and trivial-to-moderate effect sizes between conditions in core temperature (Figure 7.4B; $P= 0.14 – 1.00$; $d= 0.02 – 0.60$) or skin temperature (Figure 7.4C; $P= 0.39 – 0.67$; $d= 0.25 – 0.36$) throughout bowling efforts. Cooling reduced core temperature ($P= 0.04 – 0.05$; $d= 1.31 – 1.50$) and skin temperature ($P= 0.0001$; $d= 5.78$) during the intervention period, with large effect sizes highlighting continued thermoregulatory effects 1 h after the bowling spell ($P= 0.15 – 0.26$; $d= 0.90 – 1.15$). There were no differences in urine specific gravity between conditions for Session 1 (cooling: $1.014 \pm 0.006$ vs. control: $1.013 \pm 0.005$; $P= 0.91$; $d= 0.004$) or Session 2 (cooling: $1.013 \pm 0.006$ vs. control: $1.013 \pm 0.005$; $P= 0.78$; $d= 0.01$). Further, mean changes in nude body mass before and after the bowling spell did not differ between conditions for Session 1 (cooling: $2.45 \pm 0.68$ kg vs. control $2.21 \pm 0.57$; $P= 0.27$; $d= 0.38$) and Session 2 (cooling: $1.08 \pm 0.44$ kg vs. control $1.14 \pm 0.19$; $P= 0.70$; $d= 0.13$). Creatine kinase concentrations did not differ between conditions before or after the 10-over bowling spell (Figure 7.5A; $P= 0.55 – 0.87$; $d= 0.04 – 0.22$); but were lower in the cooling condition 24 h after the 10-over spell ($P= 0.04$; $d= 0.56$). There were no differences in C-reactive protein between conditions or over time (Figure 7.5B; $P= 0.40 – 0.76$; $d= 0.08 – 0.17$).
Figure 7.4. A Mean ± standard deviation heart rate, B core temperature and C skin temperature between Cooling and Control conditions.

* Significant difference between conditions ($P < 0.05$). ^ Large effect size between conditions (d > 0.80).
Figure 7.5. A Mean ± standard deviation creatine kinase and B C-reactive protein between Cooling and Control conditions.

* Significant difference between conditions ($P < 0.05$).
Perceptual

Ratings of perceived exertion did not differ between conditions during Session 1 or Session 2 (Figure 7.6A; $P = 0.13 – 0.80$; $d = 0.09 – 0.72$), although overall mean values were greater across both trials in Session 2 than corresponding overs in Session 1 ($P = 0.004 – 0.03$; $d = 1.36 – 2.04$). There were no differences and only small-to-moderate effect sizes in thermal sensation between conditions during either bowling spell (Figure 7.6B; $P = 0.17 – 0.84$; $d = 0.15 – 0.73$). However, cooling reduced thermal sensation during the intervention period ($P = 0.001$; $d = 3.35 – 3.36$), with a large effect size indicating sustained lowering of thermal sensation 1 h after the 10-over spell ($P = 0.07$; $d = 1.13$). Finally, perceived muscle soreness did not differ between conditions in Session 1 (Figure 7.6C; $P = 0.23 – 1.00$; $d = 0.001 – 0.05$), though was largely attenuated with cooling 1 h ($P = 0.29$; $d = 0.81$) and 24 h after the bowling spell ($P = 0.03$; $d = 2.05$).
Figure 7.6. A Mean ± standard deviation rating of perceived exertion and B thermal sensation scale and muscle soreness between Cooling and Control conditions.

* Significant difference between conditions ($P < 0.05$). ^ Large effect size between conditions (d > 0.80).
Discussion

This investigation examined the influence of mixed-method cooling on recovery of bowling performance and physiological and perceptual responses after a 10-over medium-fast bowling spell in the heat. Notably, data demonstrated that cooling maintained skill-specific (ball speed and accuracy) and physical performance (20-m sprint speed and final 5-m run-up speed) in an ensuing bowling spell the following day. Cooling effectively reduced thermal demands (heart rate, core temperature, skin temperature and thermal sensation) during the intervention period and ameliorated perceived muscle soreness and the rise in creatine kinase 24 h after Session 1. These findings demonstrate the potential benefits of cooling on recovery after medium-fast bowling in hot conditions, while also highlighting the effectiveness of mixed-method strategies as a practical cooling intervention in applied settings.

While medium-fast bowlers can maintain ball speeds and accuracy during repeated (Duffield et al., 2009a) and extended bowling spells of up to 12 overs (Burnett et al., 1995; Portus et al., 2000), the present study is the first to report a reduction in bowling performance over consecutive days in the heat. Heat strain and involuntary dehydration associated with cricket (Gore et al., 1993) have been reported as detrimental to acute skill performance during bowling spells of six overs after prior activity in the heat (Devlin et al., 2001). Further, the present data also suggest some contribution from residual fatigue in reducing medium-fast bowling performance on consecutive days in hot conditions. Specifically, reduced ball speeds are most directly affected on consecutive days, although the variability in bowling accuracy reported here could have masked improvement after an enhanced physiological and perceptual recovery. Given the improvement in bowling speeds on consecutive days after mixed-method cooling recovery (Figure 7.1), such interventions could preserve ensuing
bowling performance, demonstrating the potential benefit of cooling strategies for cricket. These findings suggest benefits for prolonged duration (4-5 days) and unlimited bowling demands of first-class competition.

Anecdotal evidence suggests an association between a controlled, ‘rhythmical’ run-up and ensuing ball speed and accuracy (Woolmer et al., 2008). Moreover, ball speeds are associated with lower-body strength (Pyne et al., 2006) and horizontal speed preceding the delivery stride (Glazier et al., 2000; Salter et al., 2007; Duffield et al., 2009a). Although medium-fast bowling performance was maintained with mixed-method cooling in Session 2, full run-up speeds did not differ between conditions in Session 2 (Figure 7.2). Further, reduced final 5-m run-up speeds between sessions in the control condition could represent reduced speed into ball delivery and a functional decline in bowling performance over consecutive days (Woolmer et al., 2008). Nevertheless, no change in run-up speeds between conditions, but reduced ball speed under control conditions, implies reduced effectiveness during the delivery stride, probably because of reduced force production in trunk flexion, rotation and/or lower-limb angular velocity during delivery (Portus et al., 2000). Accordingly, cooling interventions used after medium-fast bowling could improve perceptual and/or physiological recovery, which in turn could maintain delivery-stride speed and/or trunk force production during bowling on consecutive days.

High physiological demands and inadequate recovery between exercise bouts increase residual fatigue, ultimately reducing physical performance (Spencer et al., 2005) and increasing risk of injury (Orchard et al., 2009). While the benefits of cooling on recovery of
exercise performance are equivocal (Vaile et al., 2008b), the current data demonstrate the
effectiveness of mixed-method cooling to maintain peak 20-m sprint speeds in Session 2
(Table 7.1). However, there were no differences in counter-movement jump height at 24 h
(Figure 7.3), despite marked muscle damage and perceptual soreness experienced. These
factors appear inconsequential to jump performance and indicate the capacity for athletes to
maintain brief, high-intensity efforts regardless of recovery strategies the following day
(Dawson et al., 2005; King & Duffield, 2009). Indeed, improved physiological and
perceptual states after mixed-method cooling might be ergogenic only when exercise (test)
durations are extended. Given the low specificity to the bowling action, the present counter-
movement jump protocol could be insensitive to altered functional capacity after medium-fast
bowling performance and repeated, intermittent efforts have greater relevance in cricket.

Medium-fast bowling elicited similar cardiovascular (~75 – 85% of maximal heart rate) and
thermoregulatory (core temperature ~38.6°C) responses during a 10-over bowling spell as
those previously reported (Figure 3) (Burnett et al., 1995; Devlin et al., 2001; Duffield et al.,
2009a). Further, marked sweat losses incurred during an extended spell in the heat (2.6 –
2.9% of body mass) emphasise challenges to the maintenance of hydration status in cricketers
(Gore et al., 1993). Regardless, mixed-method cooling administered after the bowling spell
reduced thermal strain and lowered core temperature and skin temperature for the duration of
the intervention period. The application of cold therapies (in greater volumes) hastens the
reduction of physiological and thermoregulatory demands after exercise (Vaile et al., 2008a;
Pointon et al., 2012). Similarly, a greater reduction in core temperature with mixed-method
cooling occurred (~0.35°C), which is comparable to studies administering cold-water
immersion over a similar 20-min intervention period (Pointon et al., 2012). Consequently,
mixed-method cooling using multiple portable and practical techniques presents an effective strategy for faster thermoregulatory recovery after medium-fast bowling performance in field-based settings.

Noakes and Durandt (2000) highlighted muscle damage incurred via the eccentric demands of the medium-fast bowling. In the present study, indirect markers of muscle damage (creatine kinase) and inflammation (C-reactive protein) were increased immediately after the 10-over spell (Figure 7.4). Further increases in creatine kinase were attenuated at 24 h in the cooling trial, without differences in C-reactive protein concentrations. Vasoconstriction associated with cooling is thought to decrease permeability of the cellular membrane, reducing interstitial protein release and slowing uptake by the lymphatic system (Eston & Peters, 1999; Bailey et al., 2007). While these attenuated creatine kinase responses after cooling support previous research (Eston & Peters, 1999; Ingram et al., 2009; Pournot et al., 2011), the relationship between creatine kinase efflux and exercise performance is tenuous (Byrne et al., 2004). Nevertheless, mixed-method cooling after medium-fast bowling in the heat eases biochemical perturbations and allows the commencement of ensuing exercise in an enhanced physiological state. Whether this improved muscle damage contributes to the prevention/development of injury noted with increases in acute bowling loads is an avenue for future investigation (Orchard et al., 2009).

Increasing perceptual demands (perceived exertion, thermal sensation and muscle soreness) occurred throughout the 10-over spell, though perceptual demands were eased with cooling recovery, as inferred from lowered ratings of effort and soreness at 24 h (Figure 7.6). Cooling
strategies applied after exercise alleviate perceptual strain in repeated bouts of team-sport exercise (Montgomery et al., 2008; King & Duffield, 2009; Rowsell et al., 2009; Rowsell et al., 2011), possibly because of greater neuromuscular recovery and/or analgesic effects of cooling (Bailey et al., 2007). Regardless, cooling could increase the perceptual readiness of the bowler to commence an ensuing spell, as reduced muscle soreness and/or lowered perceived exertion for a given bout assists maintenance of exercise performance on consecutive days (Rowsell et al., 2011). However, familiarity and prior acceptance of cooling as an effective recovery method also suggest that a placebo effect cannot be overlooked (Beedie & Foad, 2009). Nevertheless, these results underline the perceptual benefits of a mixed-method cooling recovery, and help maintain medium-fast bowling performance in the heat on consecutive days.

In summary, the results demonstrate the recovery benefits of mixed-method cooling for medium-fast bowling performance on consecutive days after a 10-over spell in hot conditions. Cooling counteracts thermoregulatory and perceptual demands after exercise, alongside reduced creatine kinase concentrations and lower perceived exertion and muscle soreness at 24 h. Accordingly, these effects maintain ball speed and accuracy, further sustaining optimal movement speeds achieved during the final 5-m of the bowler’s run-up and between-over simulated fielding activities. Importantly, the efficacy of a mixture of smaller cooling modalities to create a larger stimulus presents a practical alternative to cold-water immersion after exercise in the heat; particularly in locations where sufficiently clean or cold water is not available. Finally, field-based practitioners should use and manipulate mixed-method cooling to create recovery strategies best suited to individual, environmental and logistical constraints.
Discussion
Overview of the Thesis

This thesis examined the use of practical, mixed-method cooling strategies for the protection and recovery from exercise- and environment-induced heat stress for medium-fast bowlers. More specifically, this thesis investigated: (1) the dosage effects of mixed-method pre-cooling on intermittent-sprint performance in hot conditions; (2) the effects of mixed-method cooling and cold-water immersion on recovery following intermittent-sprint exercise in the heat; and (3) the efficacy of mixed-method cooling on performance and recovery of medium-fast bowling in the heat. In relation to aim (1), pre-cooling dosages were assessed according to both volume (Chapter 3) and duration (Chapter 4). The most favourable mixed-method pre-cooling dose was subsequently applied under field conditions (Chapter 5) to partly address thesis aim (3). Further, in addressing thesis aim (2), Chapter 6 investigated the comparative influences of ‘gold standard’ cold-water immersion and an increasingly practical mixed-method cooling strategy on physiological and neuromuscular recovery. Finally, mixed-method cooling was administered following medium-fast bowling performance to assess next-day recovery in relation to thesis aim (3).

Summary of the Major Findings

Chapter 3 – Volume Effect of Pre-Cooling

As outlined in Chapter 3, the initial study of this thesis examined the effects of volume-dependent pre-cooling on physiological and performance outcomes for self-paced intermittent-sprint exercise in the heat. The findings demonstrate the dosage effects of pre-cooling, with increasing surface area coverage corresponding with a greater blunting of physiological load and the maintenance of a higher self-paced exercise intensity. Highlighting
this, whole-body mixed-method pre-cooling increased distances covered during hard running bouts by 12% compared to control, with 6 – 7% improvements also noted with whole-body compared to head or head and hand pre-cooling techniques. Coupled with the blunting of thermal loads (↓ HR, T_c, T_sk and TSS) during whole-body pre-cooling trials, augmented intermittent-sprint exercise performance may relate to sustained voluntary force production despite no influence on voluntary activation. It is possible then, maximising heat storage reserve through larger pre-cooling volume may assist to preserve muscular recruitment to subsequently maintain work output otherwise compromised under high thermal loads. In accordance with the thesis aim, this study indicates the importance of dose-specific responses to pre-cooling surface area volume in enhancing thermoregulatory control and sustaining intermittent-sprint exercise performance in hot conditions.

**Chapter 4 – Duration Effect of Pre-Cooling**

The second study (Chapter 4) examined the effects of duration-dependent pre-cooling on physiological and performance outcomes for self-paced intermittent-sprint exercise in the heat. Results indicate physiological, neuromuscular and performance benefits with longer mixed-method pre-cooling of up to 20 min. Similar to the aforementioned results of pre-cooling volume, despite no changes in central drive, self-paced shuttle running distances were improved by 5% after a 20 min pre-cooling intervention to correspond with a greater maintenance of MVC. Although both pre-cooling durations assisted to blunt the physiological and perceptual demands of exercise in the heat (↓ HR, T_c, T_sk and TSS), the greater maintenance of heat storage reserve observed with the longer intervention period appears important for ensuing performance benefits. Adding to the findings of Chapter 3, these data further highlight the dosage effects of mixed-method pre-cooling, with greater physiological
perturbations achieved through a longer pre-cooling duration assisting to preserve neuromuscular function and subsequent self-paced intermittent-sprint exercise.

**Chapter 5 – Pre-Cooling for Medium-Fast Bowling Performance**

In applying the findings of Chapter 3 and Chapter 4, the third study (Chapter 5) examined the physiological and performance effects of mixed-method pre-cooling on a 6-over spell of medium-fast bowling in the heat. Although no conditional differences in skill-related bowling performance (ball speed and accuracy) or run-up characteristics were observed, pre-cooling maintained between-over sprint speeds as the bowling spell progressed. Most pertinent, the 20 min mixed-method pre-cooling intervention improved thermoregulatory load as physiological (HR, Tc, Tsk and sweat loss) and perceptual responses (RPE and TSS) were reduced throughout the bowling spell. While the relatively short bowling spell may have prevented the expression of differences in skill execution, mixed-method pre-cooling provided medium-fast bowlers with lower physiological strain for a standardised bowling effort during training or competition in high ambient temperatures.

**Chapter 6 – Cooling for Recovery in the Heat**

The fourth study (Chapter 6) examined the effects of post-exercise cooling interventions on physiological, neuromuscular and perceptual recovery following intermittent-sprint exercise in the heat. These data demonstrate the dosage effects of post-exercise cooling strategies and the subsequent physiological and neuromuscular recovery. Specifically, larger physiological perturbations achieved with cold-water immersion compared to mixed-method cooling and control trials hastened the reduction in thermal strain, maintaining voluntary force and increasing central activation. Interestingly, these greater reductions in thermoregulatory
demands achieved with cold-water immersion reduced oxygenation and blood volume in the prefrontal cortex. Nevertheless, the greater recovery of MVC achieved with cold-water immersion may be attributed to a reduced post-intervention Tc and indicators of muscle damage (CK) and perceptual soreness. The cooling stimulus achieved using mixed-method techniques may aid physiological, thermoregulatory and perceptual recovery after intermittent-sprint exercise in hot conditions, though the greater physiological perturbations achieved with CWI may be required to accelerate the recovery of thermally-induced neuromuscular disturbances and maintain ensuing contractile function.

Chapter 7 – Cooling for Recovery of Medium-Fast Bowling Performance

Finally, the fifth study (Chapter 7) examined the effects of post-exercise cooling on the recovery of medium-fast bowling performance in the heat. Mixed-method cooling hastened the reduction of thermal loads during the intervention period (HR, Tc, Tsk, and TSS), effectively attenuating CK efflux and perceptual discomfort 24 h post-exercise. Importantly, these improvements in physiological and perceptual recovery may have assisted in the maintenance of skill-specific (ball speed and accuracy) and physical performance (20 m sprint speed and final 5 m run-up speed) in an ensuing bowling spell the following day. These findings demonstrate the potential benefits of post-exercise cooling on recovery following medium-fast bowling in hot conditions, whilst also highlighting the effectiveness of mixed-method strategies as a practical cooling intervention in applied settings.
Pre-Cooling for Exercise Performance in the Heat

Effects on Performance

Increasing evidence supports the efficacy of pre-cooling for intermittent-sprint exercise performance in hot conditions (Castle et al., 2006; Duffield & Marino, 2007; Duffield et al., 2009d; Skein et al., 2012). Rather than increasing exercise intensity per se, pre-cooling appears to assist in the maintenance of repeated sprint efforts and self-paced exercise intensities (Duffield & Marino, 2007; Skein et al., 2012). Results from Study 1 (Chapter 3) and 2 (Chapter 4) further support pre-cooling to maintain self-paced shuttle running distances covered between bouts of maximal intermittent-sprint exercise characteristic of medium-fast bowling. Most pertinent, however, these data demonstrate ergogenic gains achieved in relation to the dose of the cooling stimulus applied. Whole-body mixed-method pre-cooling demonstrated the greatest improvement in shuttle-running distances covered compared to part-body methods covering a smaller surface area; as did pre-cooling for 20 min compared with shorter duration exposures. Accordingly, this current evidence suggests that ideal pre-cooling dosages should maximise surface area coverage and be applied for at least 20 min to optimise potential intermittent-sprint performance benefits.

Despite the improved self-paced intermittent-sprint performance observed in laboratory conditions, mixed-method pre-cooling had limited effects on the movement characteristics of medium-fast bowling in the heat during Study 3 (Chapter 5). While these discrepancies could be explained by the standardised run-up and controlled movement patterns between overs, trends for faster sprint speeds were observed between conditions as the bowling spell progressed. Similar to reduced declines in sprint times during Study 1 and 2, this finding may highlight the lowered thermal demand of medium-fast bowling after pre-cooling, preserving muscle recruitment patterns and force output (Kay et al., 2001; Duffield et al., 2010).
Considering the relative brevity of the 6-over spell compared to the laboratory protocol (~45 min vs. 2 x 35 min), this improved physiological/perceptual response might extend the duration over which controlled intensity exercise can be maintained i.e. time to fatigue, as observed in constant-intensity time to exhaustion cycling trials (Olschewski & Brück, 1988; Lee & Haymes, 1995). The effect of pre-cooling on medium-fast bowlers under heat stress when interplayed with competitive factors (e.g. opposition batsmen, tactics, fielding activities, game format and context) during prolonged or repeated spells remains to be elucidated; however, findings here would suggest some potential benefit for use.

Earlier reductions in exercise intensity are commonly reported in hot conditions (Marino, 2004), though declines in sport-specific neuromotor skill performance are also a recognised concern (Bergeron et al., 2012). The ergolytic effects of challenging environmental conditions confronting cricketers likely relate to elevated thermal loads and sub-optimal fluid replacement (Gore et al., 1993); previously demonstrated to manifest in lowered accuracy of medium-fast bowlers (Devlin et al., 2001). Yet despite the blunted \( T_c \) responses and preservation of hydration status achieved with pre-cooling in Study 3, no changes were apparent between conditions in ball speed or accuracy during the 6-over spell. While limited effects of pre-cooling have been shown on sport-specific skills in tennis (Hornery et al., 2007a) and soccer (Yasumatsu et al., 2008), the blunted responses to relatively mild physiological demands (HR, \( T_c \), and \( T_{sk} \)) demonstrated here also appear inconsequential to skill execution in medium-fast bowlers. However, a limitation to Study 3 is the absence of a competitive scenario, as opposition batsmen were removed to allow ball speed and accuracy to be directly quantified. Accordingly, given the lowered perceptual strain experienced, the
psychophysiological benefits of pre-cooling could still maintain anticipation and decision making (Phillips et al., 2010), of relevance to medium-fast bowlers.

**Mechanistic Underpinnings**

Corresponding with improved self-paced intermittent-sprint performance, greater pre-cooling doses (volume and duration) maintained neuromuscular function. High thermal loads have been well documented to impair contractile force and voluntary activation following both passive (Morrison et al., 2004; Thomas et al., 2006) and exercise-induced hyperthermia (Nybo & Nielsen, 2001a; Périard et al., 2011a). Accordingly, the greater reductions in thermal strain (T_c, T_â, HR, and TSS) achieved with the largest pre-cooling doses (i.e. whole-body mixed methods pre-cooling for 20 min) in Studies 1 and 2 may explain the higher MVC force noted during and after exercise in the heat. This sustained muscle function could well elucidate the higher self-paced running distances accumulated and the maintenance of post-exercise MVC despite greater work completed (Duffield et al., 2010). However, similarly reduced VA between pre-cooling dosages during and after exercise suggests this thermally protected voluntary force to be unlikely of central or peripheral origins alone. Rather, it would seem that the sustained voluntary force demonstrated with greater pre-cooling might have facilitated the maintenance of motor unit discharge below the neuromuscular junction (Bigland-Ritchie et al., 1986; Enoka & Stuart, 1992). While this explanation may stand, end-sprint phenomenon observed in sprint times is indicative of feed-forward/feedback controls and likely highlights the integration of physiological and perceptual responses to explain dose specific maintenance of muscle recruitment and exercise intensity (Tucker et al., 2004; Duffield et al., 2010; Marino, 2011).
The performance benefits of pre-cooling in the heat are traditionally attributed to the lowered cardiovascular strain and higher maximal oxygen uptake ($\text{VO}_{2\text{max}}$) achieved at lower body temperatures (Schmidt & Brück, 1981; Olschewski & Brück, 1988; Lee & Haymes, 1995). Greater heat removal before exercise increases centralised blood volume via reduced sweat rates and lower heat dissipation required at the periphery (Wendt et al., 2007). Accordingly, the blunted HR responses observed during intermittent-sprint exercise (Studies 1 and 2) and medium-fast bowling (Study 3) are common after pre-cooling (Wegmann et al., 2012), and likely represent maintained stroke volume, cardiac output and venous return (González-Alonso et al., 1999; Arngímsson et al., 2004). Interestingly, although body fluid deficits were reduced with larger pre-cooling dosages, the lack of change in CNS drive between conditions suggests that hydration status alone may not directly regulate motor cortical excitability as previously proposed (Montain & Tharion, 2010). Yet these lowered cardiovascular demands may still explain the higher self-paced hard running distances covered in Studies 1 and 2 by reducing skin blood flow requirements and increasing venous tension to increase cardiac filling, maximal cardiac output, and thus $\text{VO}_{2\text{max}}$ (Cheuvront et al., 2010). Accordingly, it is plausible that greater cardiovascular control achieved with pre-cooling may sustain muscle blood flow (González-Alonso & Calbert, 2003), maintaining voluntary force and self-selected exercise intensities through a higher preservation of oxygenation and fuel substrate availabilities.

Of importance to the current pre-cooling data are the lowered perceptual ratings of exertion and thermal strain in relation to the pre-cooling doses applied. Our findings demonstrate lower RPE despite higher self-paced work completed in both laboratory-based investigations
(Studies 1 and 2), perhaps reflective of the lower biological demands incurred in the maintenance of homeostasis (Noakes et al., 2005). While the highly paced and rhythmical nature of medium-fast bowling run-up may have prevented the detection of performance benefits, lower RPE values were reported for the same exercise intensities performed (Study 3). This higher subjective difficulty in maintaining bowling performance in the control condition (i.e. RPE) may relate to the linear relationship between increasing $T_c$ and electroencephalogram (EEG) signaling in the prefrontal cortex (Nybo & Nielsen, 2001c). Whilst largely speculative, altered F3 $A_{\alpha d}/A_{\beta}$ indices reflected in higher RPE under heat stress could decrease arousal and impair motor activity and power output (Nielsen et al., 2001). Although not assessed in the current series of investigations, EEG frequency shifts without altered motor unit recruitment or discharge rates in hot conditions entails change in the CNS rather than in muscle activity per se (Nybo & Nielsen, 2001c). Therefore, it is suggested that lowering body temperatures using pre-cooling improves conscious sensation of thermal comfort during bowling-specific intermittent-sprint activity, easing the mental requirements of performance and thus manifesting in a lower RPE during exercise in the heat (Marcora et al, 2009).

Finally, although similar reductions in thermal loads were observed with pre-cooling throughout the present investigations, gains in intermittent-sprint performance evident under laboratory conditions (Studies 1 and 2) were not replicated during medium-fast bowling performance in the field (Study 3). It is notable then, that the highly controlled and skill-focused movement patterns of medium-fast bowlers examined in Study 3 restricts the expression of pacing strategies likely accountable for the greater high-intensity shuttle running achieved in the laboratory. Indeed, the effects of pre-cooling may be dependent on
exercise type (Wegmann et al., 2012), thus matched work rates in Study 3, both through
design (between overs) and default (skill requirements), may account for these divergent
findings between laboratory (Studies 1 and 2) and field-based investigations (Study 3). While
speculative, when combined with extended periods of passive heating during fielding
activities, pre-cooling could still maintain medium-fast bowling performance, particularly
where lower RPE and thermal strain for a given work rate is reported to extend time to
fatigue (Olschewski & Brück, 1988; Lee & Haymes, 1995). As such, pre-cooling for
medium-fast bowling may represent a similar model to constant-intensity exercise protocols
(Olschewski & Brück, 1988; Lee & Haymes, 1995), and rather than increase work performed
within a bout, extend the duration at which certain exercise intensities can be performed.
How this might interact with any protective regulation of exercise intensity in relation to
elevated body temperatures (Tucker et al., 2004) and/or the maintenance of skill performance
of medium-fast bowlers is unknown and warrants further investigation.

Post-Exercise Cooling for Recovery in the Heat

Effects on Performance

The high thermal demands of exercise in the heat are well documented to suppress exercise
performance (González-Alonso et al., 1999; Marino, 2004; Tucker et al., 2004; Drust et al.,
2005), with a faster removal of heat strain suggested to hasten the return of optimal CNS
functioning (Duffield, 2008). Importantly, novel findings from Study 4 demonstrate the
efficacy of post-exercise cooling, as cold-water immersion improved the acute recovery of
MVC by 12.5 ± 8.7% compared to control immediately post-intervention. Further, although
not statistically significant ($P = 0.07$) and 6.3 ± 8.3% less effective than cold-water
immersion, it is salient that the rate of MVC recovery post-intervention achieved using mixed-method cooling was also 6.2 ± 9.3% faster than control. These acute recovery benefits were sustained 1 h post-exercise in cold-water immersion trials (↑ 12.7 ± 11.7% and 16.3 ± 10.7% vs. mixed-method cooling and control, respectively), though benefits of mixed-method cooling appear to have dissipated with only small effects remaining (↑ 3.8 ± 10.7% vs. control; \( P = 0.31 \)). Accordingly, it is not surprising that no differences were observed in CMJ performance with mixed-method cooling after a 10-over medium-fast bowling spell in the heat (Study 5). Nevertheless, the acute gains in knee-extensor MVC following post-exercise cooling found in Study 4 support the findings of Vaile et al. (2008a) and Peiffer et al. (2010a) who report post-exercise cooling to maintain power output during repeated cycling bouts. Collectively, these data demonstrate potential ergogenic gains achievable using post-exercise cooling strategies and may be of particular relevance for athletes undertaking multiple same-day sessions whereby training or competitive success could be compromised by sustained suppression of neuromuscular performance in the heat.

Additionally, this thesis highlights the efficacy of post-exercise cooling in maintaining next-day neuromuscular (Study 4) and intermittent-sprint performance (Study 5) following medium-fast bowling related activity in hot conditions. Similarly, Pournot et al. (2011) recently showed a 15 min cold-water immersion post-exercise recovery strategy to attenuate the suppressed performance state of peak power output, knee-extensor MVC and counter-movement jump height 24 h after repeated high-intensity exercise bouts. Further, Study 4 demonstrates a greater maintenance of MVC 24 h post-exercise using a cold-water immersion recovery, increasing voluntary force production by 8.7 ± 10.5% and 16.1 ± 20.5% compared to mixed-method cooling and control trials respectively. These findings support cold-water
immersion as the ‘gold standard’ in the treatment of exercise- and environment-induced heat stress (Casa et al., 2007); however, the recovery benefits achieved in Study 5 also demonstrate the available performance benefits achieved using ecologically valid alternatives to improve field-based convenience. Mixed-method cooling facilitated a higher peak sprint speed throughout simulated fielding exercise 24 h after a 10-over medium-fast bowling spell in the heat. Considering the need for cricketers to complete intermittent-sprint running activities on consecutive days, these data reiterate the benefits of post-exercise cooling interventions on next-day recovery (Bailey et al., 2007; Vaile et al., 2008b; Ingram et al., 2009; Pournot et al., 2011). Collectively, these data could advocate the use of mixed-method cooling to ease difficulties surrounding the administration of whole-body cold-water immersion, but also indicates different potential effects of cold therapies in relation to the recovery of the specific exercise task.

Finally, and arguably of greatest importance, the recovery benefits of mixed-method cooling are not restricted to purely physical efforts (i.e. MVC or intermittent-sprint exercise). Rather, the faster return of optimal functioning shown in Study 5 assisted to maintain run-up speed and associated ball release speed (Glazier et al., 2000; Duffield et al., 2009a). Several studies have examined post-exercise cooling strategies within sports-specific training or competition contexts on consecutive days; though definitions of performance have related to match movement patterns (Montgomery et al., 2007; Rowsell et al., 2009; Rowsell et al., 2011) without consideration for any influence on skill-related components of sports performance. Further, to our knowledge, this data is the first to demonstrate the benefits of cooling strategies on skill performance during (Hornery et al., 2007a) or following exercise. However, given the importance of lower-body power (Pyne et al., 2009) and run-up speed
leading into the delivery stride (Glazier et al., 2000; Salter et al., 2007; Duffield et al., 2009a), cooling-induced maintenance of voluntary force (Study 4) and intermittent-sprint performance (Study 5) may reflect a greater relevance of cooling recovery for skill execution incorporating high physical contributions. While the benefits for medium-fast bowling accuracy could have been masked by external factors (i.e. seam, swing, surface variation etc.), demonstrated improvements in contractile unit function might also influence motor control (Rampinini et al., 2009). The effects of post-exercise cooling on the recovery of fine motor skills characteristic of medium-fast bowling (e.g. dexterity and coordination of hand and finger movements) are yet to be examined, though are highly relevant to the recovery of sports performance.

**Mechanistic Underpinnings**

Recent hypotheses relating to the recovery benefits of post-exercise cooling techniques following passive and/or exertional heat stress relate to a lessening of thermal strain resulting in improved CNS drive, otherwise inhibited under hyperthermic conditions (Duffield, 2008; Pointon et al., 2012). In support of this premise, Study 4 demonstrates a faster return of MVC force, central activation and muscle recruitment patterns post-intervention and 1 h post-exercise in cold-water immersion trials. Thomas et al. (2006) have previously shown the recovery of voluntary activation and subsequent force production to occur proportionately with reductions in elevated $T_c$ independent of muscle temperature within a passive heating/cooling model. Additionally, this thesis highlights the importance of heat loss (threshold and/or rate of cooling) in the recovery of neuromuscular performance; as decreased absolute $T_c$ did not influence voluntary force and activation (Study 4) or counter-movement jump height (Study 5) using mixed-method cooling. Further, in contrast to
aerobic exercise performance (Sawka et al., 2012), these data show $T_{sk}$ not to factor in the acute maintenance of brief voluntary force production (Morrison et al., 2004; Thomas et al., 2006), as dose-specific reductions in $T_{sk}$ demonstrated in Study 4 had no influence on knee-extensor MVC. Nevertheless, these findings provide further evidence for the central contributions to the suppression of voluntary force following exercise in the heat, and whilst the mechanisms require further investigation, cooling strategies designed to hastily reduce $T_c$ may improve acute exercise recovery via the return of motor outflow.

Peripheral reflexes associated with cooling may interact with central commands underlying recovery from intermittent-sprint exercise in the heat (Williamson, 2010). As cooling enables greater heat losses to alleviate high thermal demands, peripheral vasoconstriction increases centralised blood volume, easing cardiovascular strain ($\downarrow$ HR in Study 4 and 5) via larger stroke volumes, cardiac output and venous return (Bonde-Petersen et al., 1992). Although this redirected regional blood flow may adversely affect the removal of metabolic byproducts (Peiffer et al., 2009a), Vaile et al. (2011) demonstrate greater performance maintenance and no differences in leg blood flow during an ensuring exercise bout 40 min after cold-water immersion recovery. Indeed, the collective reductions in HR, $T_c$ and $T_{sk}$ reported in this thesis may also relate to a larger centralised blood volume; and considering the improved recovery of voluntary force and activation achieved with cold-water immersion, may have relevance to such performance outcomes. Nevertheless, NIRS data from Study 4 also highlights cold-water immersion to alter cerebral haemodynamics, decreasing blood flow ($[O_2Hb]$), volume ($[THb]$) and oxygenation (TSI). Given the importance of cerebral oxygenation and neuronal excitability on CNS drive (Rupp & Perrey, 2008), these alterations in cerebrovascular regulation with cooling seem disconnected to the recovery of voluntary force in the heat.
Thus, whether circulatory shifts in response to cooling are an acute performance mechanism or simply reflex response remains unclear and requires further investigation.

Despite the potential benefits of post-exercise cooling on acute (1 – 2 h) (Pointon et al., 2012) and intermediate (24 – 72 h) (Vaile et al., 2008b; Ingram et al., 2009) recovery of neuromuscular force, underlying mechanisms appear biphasic; initially centrally-mediated as related to physiological perturbations (Pointon et al., 2012), and secondly pertaining to peripheral contractile structure (Wilcock et al., 2006; Leeder et al., 2012). Stemming from sports medicine treatments of soft-tissue injury (Orchard et al., 2008), considerable attention has been focused on post-exercise cooling to attenuate expression of indirect biochemical markers of muscle damage and inflammation (Eston & Peters, 1999; Bailey et al., 2007; Halson et al., 2008). Cooling-induced vasoconstriction decreases cellular, lymphatic and vascular permeability to attenuate interstitial fluid release and subsequent inflammatory events (Wilcock et al., 2006; Leeder et al., 2012). Importantly, cold-water immersion and mixed-method cooling reduced CK 24 h post-exercise in Studies 4 and 5 respectively. Further, although no significant differences were apparent in CRP concentrations, a lower cortisol response after both cooling interventions 1 h post-exercise in Study 4 may reflect a reduced anti-inflammatory response as contractile unit structure is maintained. It is notable then that lowered indirect anti-inflammatory and muscle damage markers follow similar patterns of change to perceptual soreness, voluntary force and medium-fast bowling performance at 24 h. While it is fortuitous to link biochemical protein and metabolite concentrations with exercise performance (Brancaccio et al., 2007), elevated CK responses could alternatively derive from higher metabolic costs rather than greater muscle damage associated with environment and/or exercise (Baird et al., 2012). Regardless, this lower
biochemical stimulation and expression noted after cooling likely demonstrates reduced muscle disruption and/or enhanced repair indicative of a higher physiological status (Baird et al., 2012).

It is noteworthy that divergent recoveries of exercise performance were apparent using mixed-method cooling in Studies 4 and 5. Specifically, no differences were apparent in the return of isolated, isometric knee-extensor MVC force, yet contrastingly, mixed-method cooling improved the recovery of dynamic, whole-body medium-fast bowling activity. While some caution must be advised when directly comparing separate participant cohorts, collectively they highlight differing effects of cooling techniques and/or exercise modalities on task-specific recovery. Assessment of single-leg MVC and VA may not provide a true reflection of whole-body capacity, though it does provide an indication of skeletal muscle function and CNS drive, which would be suggested to influence dynamic exercise performance (Vaile et al., 2008a; Peiffer et al., 2010b). Even considering the differences in exercise modes, it is somewhat surprising that the effects of mixed-method cooling were not distinguishable in isolation rather than in dynamic movement bouts as per Pointon et al. (2011). While the influence of a placebo effect cannot be overlooked (Clark et al. 2000; Beedie 2007), similar RPE values and lowered muscle soreness corresponding with a lowered creatine kinase response could reflect improvements in contractile unit structure, potentially maintaining medium-fast bowling performance. Regardless of the perceived benefits of mixed-method cooling treatment (Bailey et al. 2007; Halson et al. 2008; Rowsell et al. 2009), recovery benefits of post-exercise cooling appear to be task-specific and dependent on the intermediate recovery assessments administered.
Conclusions

The findings presented in this thesis demonstrate and support the efficacy of cooling strategies in the prevention and recovery from exercise- and environment-induced heat stress for medium-fast bowlers. Importantly, the application of sufficient cooling stimuli increases the thermal gradient to seemingly attenuate inhibited voluntary force and so maintain and/or hasten the recovery of neuromuscular function and exercise performance in the heat. Accordingly, this thesis demonstrates dose-specific improvements in self-paced intermittent-sprint exercise performance as greater mixed-method pre-cooling volume and duration reduced physiological and perceptual loads to sustain MVC force, without influencing VA between conditions. Similarly, the acute recovery benefits of post-exercise cooling appear to reflect the rate of endogenous heat loss; though in contrast to pre-cooling investigations, the recovery of voluntary force was accompanied by the return of central activation and muscular recruitment patterns. Importantly, these data show mixed-method cooling to ease the physiological and perceptual demands of medium-fast bowling in the heat and improve next day recovery, presenting cricketers with practical means to maintain performance and recover from the demands of hot environmental conditions.
Summary and Conclusions
Overview

This thesis aimed to examine the effects of practical mixed-method cooling interventions for the protection and recovery of medium-fast bowling exercise in the heat. The outcomes of this research as addressed throughout this thesis are summarised as follows:

Research Aims – Study 1

1. *This study aimed to examine the effects of mixed-method pre-cooling volume on self-paced intermittent-sprint performance and physiological responses in the heat.*

Dose-specific responses were noted with respect to improvements in self-paced intermittent-sprint performance in the heat, as increasing surface area coverage of pre-cooling blunted the physiological and perceptual responses to exercise in the heat. As such, the larger the pre-cooling volume administered (i.e. whole-body > head + hand > head > control), the larger the reduction in thermal demands (↓ T_c, T_sk, HR, sweat losses, perceived exertion and thermal sensation) and the greater the maintenance in exercise intensity. These dosage effects were particularly evident in ‘hard’ running efforts, as higher self-selected work rates were maintained with the greater pre-cooling volume applied.

2. *To determine the effects of pre-cooling volume on voluntary force and evoked twitch properties and their relationship to exercise performance in the heat.*

Pre-cooling sustained voluntary force production despite the increase in self-paced shuttle running completed. Although the associations between an isometric knee-extensor MVC and
self-paced intermittent-sprint exercise may be tenuous, large trends for a faster TPt mid-exercise during whole-body pre-cooling trials may be reflected in the maintenance of 15 m sprint times compared to control. However, despite significant differences and large ES indicating greater ‘hard’ running distances covered in whole-body and head + hand pre-cooling trials during Spell 1, no effects were evident on MVC torque mid-exercise. Further, higher exercise intensities were performed in all pre-cooling trials throughout ‘hard’ running efforts in Spell 2, though the improved maintenance of post-exercise peak torque evident with larger pre-cooling volumes was not replicated when pre-cooling the head only. Although larger pre-cooling volumes could facilitate the maintenance of CNS drive resultant of an increased thermoregulatory control, these inconsistent findings indicate athletic benefits of pre-cooling to not be of central origins alone. Rather, considering the similar reductions in voluntary activation for greater distances covered it is speculated that pre-cooling facilitates greater self-paced intermittent-sprint performance via the interaction of afferent and efferent signaling otherwise inhibited in high ambient conditions.

**Research Aims – Study 2**

1. *This study aimed to examine the effects of mixed-method pre-cooling duration on self-paced intermittent-sprint performance and physiological responses in the heat.*

Mixed-method pre-cooling improved the physiological and perceptual responses of self-paced intermittent-sprint exercise in the heat (↓ Tc, Tsk, HR, sweat losses, and TSS), sustaining lower rates of heat storage for the entirety of the exercise protocol. While the improvements in thermoregulatory strain during exercise were achieved proportionately to the duration of the pre-cooling application (20 min > 10 min > control), performance gains
were only observed after a 20 min pre-cooling intervention. Accordingly, 20 min of mixed-method pre-cooling demonstrated faster 15 m sprint times than control, and minimising performance declines as exercise continued (i.e. during Bout 2). Higher self-selected exercise intensities were also sustained during ‘hard’ running bouts with 20 min of mixed-method pre-cooling compared with other conditions; perhaps highlighting a dosage threshold required for pre-cooling to benefit self-paced intermittent-sprint exercise in hot conditions.

2. To examine the effects of mixed-method pre-cooling duration on voluntary force and evoked twitch properties and their relationship to exercise performance in the heat.

Similar to the abovementioned surface area dosage, the effects of cooling duration on exercise performance resulted in larger alterations in neuromuscular function after 20 min compared to 10 min mixed-method pre-cooling and control, respectively. Greater MVC peak torque recorded mid- and post-exercise during 20 min pre-cooling trials may infer the preservation of voluntary force to sustain self-paced intermittent-sprint performance, particularly at high intensities, compared to shorter intervention durations. Nevertheless, higher mid-exercise MVC force following a 10 min pre-cooling intervention demonstrated no apparent influence on any sprint or shuttle run variable compared to control. Longer mixed-method pre-cooling durations (up to 20 min) may improve voluntary force during exercise in the heat, though central and/or peripheral mechanisms are blurred as changes in voluntary activation are veiled by higher work rates.
Research Aims – Study 3

1. This study aimed to examine the physiological, perceptual and performance effects of mixed-method pre-cooling on a 6-over spell of medium-fast bowling in the heat.

Mixed-method pre-cooling blunted the physiological (T_c, T_sk, HR and sweat losses) and perceptual demands (RPE and TSS) of medium-fast bowling performance in hot conditions. Although this improvement in thermoregulatory control did not affect skill-related bowling performance (ball speed, accuracy and run-up speed), between-over sprint speeds were faster during pre-cooling trials after Over 4. Further, considering the relative brevity of a 6 over spell in the context of a cricket innings, particularly at first-class level, reductions in physiological and perceptual strain achieved with pre-cooling could influence repeated bowling spells or hasten recovery to maintain performance during ensuing sessions.

Research Aims – Study 4

1. This study aimed to examine the effects of post-exercise cooling interventions on physiological, neuromuscular and perceptual recovery following intermittent-sprint exercise in the heat.

Post-exercise cooling demonstrated dose-specific reductions (cold-water immersion > mixed-method cooling > control) in physiological (T_c, T_sk and HR) and perceptual strain (TSS and MS) in hot conditions. Interestingly, improvement in the recovery of MVC force was only observed in the cold-water immersion trial, possibly suggesting the existence of a cooling threshold required for ergogenic benefits to be achieved. Larger alterations in physiological responses may represent potential mechanisms during the recovery time-course, as greater
voluntary force production were aligned with higher central activation ratios after the reduction of endogenous thermal loads post-intervention and 1 h post-exercise. However, with the return of voluntary activation to baseline levels in all conditions by 24 h post-exercise, gains in force output may reflect the greater maintenance of contractile unit structure as suggested by lower perceived soreness, muscle damage (creatine kinase) and indirect anti-inflammatory markers (cortisol). Thus, although mixed-method cooling assisted to alleviate the physiological and perceptual symptoms of exercise- and environment-induced heat stress, only cold-water immersion was of benefit to the recovery of neuromuscular function after self-paced intermittent-sprint exercise in the heat.

2. To examine the effects of post-exercise cooling interventions on cerebral oxygenation and subsequent neuromuscular function.

The current data highlight an inverse relationship between an exacerbated reduction in cerebral oxygenation following exercise in the heat and improved recovery of voluntary force and activation using cooling techniques. Post-exercise cooling reduced $[O_2Hb]$ and $[THb]$ in both cooling trials, though somewhat counter intuitively the larger alterations in circulatory characteristics elicited using cold-water immersion reduced TSI despite an improvement in neuromuscular function post-intervention. Accordingly, regardless of the previously demonstrated effects of cerebral oxygenation on motor activation, this appears inconsequential to the recovery of exercise performance with these haemodynamic changes likely representing a reflex response to the cooling stimulus and not a direct mechanism affecting moto-neural regulation per se.
Research Aims – Study 5

1. This study aimed to examine physiological, perceptual and performance effects of mixed-method post-exercise cooling on recovery after a 10-over medium-fast bowling spell in the heat.

Mixed-method cooling administered following an extended spell of medium-fast bowling in hot conditions hastened the reduction of high thermal loads (HR, $T_c$, $T_{sk}$ and TSS); further, blunting creatine kinase concentration, muscle soreness and perceived exertion 24 h post-exercise. While this improved rate of physiological and perceptual recovery demonstrated limited effects on countermovement jump performance, mixed-method cooling improved next-day bowling performance as reflected through a greater maintenance of ball speeds, run-up characteristics and peak sprint speeds. Accordingly, post-exercise recovery protocols including mixed-method cooling techniques may sustain medium-fast bowling performance in the heat on consecutive days, especially pertinent for first-class cricketers participating in multiple-day match formats.

Summary and Conclusions

Extended periods of high-intensity exercise required of medium-fast bowlers may inherently compromise performance where competition is undertaken in thermally challenging environments. The combination of increasing metabolic heat gain and lessening environmental heat dissipation in hot conditions exacerbates thermoregulatory demands of medium-fast bowling, invoking elevated sweat losses (Gore et al., 1993), decreased performance (Devlin et al., 2001) and greater risk of heat-related illness (Driscoll et al., 2008;
Finch & Boufous, 2008). Cooling interventions administered before or after exercise in the heat may ease thermal strain, assisting to maintain performance and hasten recovery (Duffield, 2008). Importantly, the current data demonstrate dose-specific responses of cooling on physiological and performance benefits, as lower demands on heat storage reserves decrease body temperatures and cardiovascular strain to maintain force production and CNS drive. Larger mixed-method pre-cooling volumes for extended durations of practical relevance (20 min) blunted physiological and perceptual responses to exercise- and environment-induced heat stress, easing declines in intermittent-sprint performance and sustaining high intensity pacing strategies associated with greater neuromuscular function.

Differences in recovery time-course were observed between cold-water immersion and mixed-method cooling; though similar to pre-cooling, results indicate greater improvement in neuromuscular recovery where larger alterations in physiological state were achieved. Accordingly, these findings suggest the rate of heat loss as important to the acute recovery of thermally inhibited central activation and muscle recruitment. Furthermore, cooling may also alter peripheral circulatory characteristics easing inflammatory responses to exercise-induced muscle damage. Most pertinent, however, is that mixed-method cooling strategies were demonstrated to have high practical relevance in applied settings, reducing the physiological and perceptual demands of medium-fast bowling and preserving skill-specific and physical performance in the heat on consecutive days.
Practical Applications

- The reduced physiological demands of exercise in hot conditions achieved using larger pre-cooling interventions seemingly preserves neuromuscular function, maintaining both intermittent-sprint performance and the selection of higher exercise intensities during self-paced exercise.

- Mixed-method pre-cooling has physiological and perceptual benefits for medium-fast bowling performance in the heat. It is speculated that the resultant lowered thermal demands may extend time to fatigue and/or allow the bowler to commence subsequent bowling spells/training sessions in an enhanced physiological state.

- Post-exercise cooling presents an effective means for the acute recovery of voluntary force and activation, and the protection of contractile unit integrity. Nevertheless, these benefits are achieved specific to the dosage administered, with cold-water immersion being 13% and 9% more effective than mixed-method cooling 1 h post- and 24 h post-exercise, respectively.

- Mixed-method cooling assists to hasten the removal of thermal strain after a 10-over medium-fast bowling spell in hot conditions, subsequently reducing physiological strain and improving next-day mean ball speed (4.1 km·h\(^{-1}\)) and peak sprint speed (1.6 km·h\(^{-1}\)).

- Mixed-method cooling presents a practical alternative to traditional whole-body immersion techniques for medium-fast bowlers. Whilst the efficacy of cold-water immersion for the protection or recovery of exercise- and environment-induced heat
stress is clear, the manipulation of mixed-method cooling volume and duration may improve logistical and environmental concerns of practitioners in the field.

**Recommendations for Future Research**

- Although the acute benefits of cooling for the protection and recovery of exercise performance in the heat are being increasingly demonstrated, the chronic effects of repeated cooling applications on training adaptation requires attention. Whilst limited without additional inflammatory, cytokine and hormonal markers, the current data demonstrate pre- and post-exercise cooling to alter biochemical expression of muscle damage and catabolic profiles associated with physiological adaptation to training stimulus. This potentially unfavorable side-effect of cooling warrants investigation, with particular focus on the effects of training mode (aerobic and resistance), application time (pre-, mid- and post-exercise) and cooling technique (internal and external) on muscle performance and cellular adaptation.

- While declines in exercise performance in the heat can be alleviated using pre-cooling techniques, reducing thermoregulatory demands also reduces cardiovascular and metabolic overload required for training adaptation. A hot and humid training environment is likely to increase the physiological strain of exercise but also increase time to recovery. Accordingly, given the use of cooling strategies and training sessions in temperature-controlled environments at the elite level, greater understanding of the thermoregulatory influences on principles of training, overload and recovery are required to best access the physiological adaptation desired.
• Considering the role of cerebral oxygenation on CNS drive and exercise performance reported in hot (Rasmussen et al., 2010) and hypoxic conditions (Subudhi et al., 2009), contrasting findings in the recovery of MVC force after CWI in Study 4 (Chapter 6) is perplexing. The current methodology is limited in explaining this occurrence; particularly whether vasoconstriction of cerebral blood supply is reducing arterial flow and/or what effect this has on the neuronal uptake to support a lower [O$_2$Hb] concentration. The use of ultrasound (blood flow) and electroencephalogram monitoring (neuronal activity) may assist to further elucidate this relationship between cold-water immersion and the recovery of voluntary activation after exercise- and environment-induced heat stress.

• The current data highlight the potential benefits of cooling for the protection and recovery of exercise- and environment-induced heat stress in medium-fast bowlers. However, both the laboratory and controlled field-based study designed reported here do not reflect competitive scenarios and thus additional study of pre- and post-exercise cooling during an actual cricket match is required.
References


Backx, K., McNaughton, L., Crickmore, L., Palmer, G., & Carlisle A. (2000b). The effects of differing environmental conditions on the performance and recovery from high-


Participant Information and Consent Forms
INFORMATION SHEET

Effects of pre-cooling interventions on intermittent sprint performance in the heat.

Thank you for expressing interest in this research. Please read and retain this information sheet. Should you have any questions regarding this study please do not hesitate to contact:

**Geoffrey Minett** (Principal Investigator)
PhD Student
School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW 2795
Tel: 0437 597 473
Fax: (02) 6338 4065
Email: gminett@csu.edu.au

**Dr Rob Duffield** (Supervisor)
School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW 2795
Tel: (02) 6338 4939
Fax: (02) 6338 4065
Email: rduffield@csu.edu.au

**Prof Frank Marino** (Co-Supervisor)
School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW 2795
Tel: (02) 6338 4268
Fax: (02) 6338 4065
Email: fmarino@csu.edu.au

**Background Information**
Major cricket competitions occur in thermally stressful environments placing players at increased risk of heat stress and associated performance and heath related decrements. Reducing skin and core temperature via cooling interventions may assist to prevent or alleviate symptoms of exercise- and environment-induced heat stress. Despite physiological and performance based interest in whole- and part-body cooling interventions, the underlying mechanisms remain unknown. Furthermore, the use of laboratory based research with whole-body cold-water immersion strategies reduces practicality for athletes in the field. As a result, research is lacking on the application of small and practical mixed-method techniques in comparison with whole-body cold-water immersion for pre-cooling in the heat.
While recent research reports performance improvements for exercise in the heat following pre-cooling interventions (Duffield & Marino, 2007), little evidence exists to demonstrate the physiological and performance implications of various mixed-method approaches to attain the greatest ergogenic result.

**Purpose**
To determine the volume of part-body pre-cooling that is required to elicit physiological and performance responses for use in field environments.

**Participant Requirements**

**Study Design**
Participants will be required to be well-trained team sport athletes, currently completing ≥ 2 training sessions and competing on a weekly basis. All testing sessions will be conducted at the Exercise and Sports Science Laboratories (S21). **Participants will be required to be in a rested state, maintain a similar dietary pattern and not consume any alcohol 24 h pre-, or caffeine or food in the 3 h pre-testing.**

The first testing session will be a familiarisation session to ensure participants are familiar with experimental measures such as the exercise protocol, neuromuscular function, perceptual ratings and cooling interventions. A Dual-Energy X-ray Absorptiometry (DXA) scan will provide analysis of participant body composition. Following this session, all proceeding sessions will be identical, with the pre-cooling intervention the only variable. During these sessions tests of neuromuscular function and blood draws will be included to assess heat shock proteins, cell growth, indicators of central fatigue and anaerobic metabolism.

**Pre-Cooling Interventions**
Following familiarisation, this investigation will be conducted over 4 data collection sessions. Pre-exercise, participants will be cooled for 15 min with methods involving:

- **Control:** No pre-cooling intervention.
- **Hand pre-cooling:** Pre-cooling of the hand (CoreControl, AVAcore Technologies).
- **Head pre-cooling:** Pre-cooling of the head, neck, shoulders and face with cold wet towels.
- **Mixed-method whole-body pre-cooling:** Pre-cooling via hand, torso, quadriceps and head.

**Exercise Protocol**
Following resting measures and pre-cooling intervention, participants will perform an intermittent-sprint running protocol comprising of 2 x 35 min identical sessions, separated by a 15 min recovery period. Exercise will occur in controlled environmental conditions of 33°C and 40% relative humidity. The intermittent-sprint running protocol will consist of a series of 6 x 15 m maximal efforts intertwined with 5 min bouts of self-paced activity at prescribed intensities, designed to incorporate the movement requirements for cricket fast bowlers.

**Data Collection**

**Neuromuscular Function:** Measures of muscle strength and activation will be attained pre-intervention, pre-exercise, mid-exercise and post-exercise using an endurance muscular voluntary contraction (MVC) protocol with electrical stimulation of the femoral nerve at the inguinal fold. This procedure requires participants to maximally contract their quadriceps muscle against a fixed resistance, to which a short (<0.3 s) electrical stimulus will be applied. This will also occur during maximal contractions, in which the electrical stimulus will be applied at peak force during the contraction.

**Body Temperature** Core temperature will be measured with a telemetric pill (VitalSense, Mini Mitter, USA), ingested 4 h pre-exercise to ensure passing into the gastrointestinal tract. Participants will be advised that they cannot have an MRI while the pill is in the body until it has been passed and will also be given a bracelet warning as a reminder. Skin temperature will be measured at the sternum, mid-forearm, mid-quadriceps and medial calf via telemetric patches (VitalSense, Mini Mitter, USA). Core temperature and skin temperature will be recorded pre-intervention, post-intervention, pre-exercise and at 5 min increments throughout the exercise protocol via a hand held monitor telemetrically receiving core pill and skin patch measurements. Muscle temperature within the quadriceps (vastus lateralis) will be measured pre-intervention, post-intervention, mid-exercise and post-exercise. Anesthetic skin cream (emla, AstraZenetec, North Ryde, Australia) will be applied.
around the intended puncture site prior to the insertion of a sterile 22-gauge needle and associated thermistor into the muscle belly.

**Exercise Performance:** Exercise performance will be determined via 15 m sprint times and distances covered during sub-maximal exercise bouts. Sprint times will be measured using an infra-red timing system (Speed-Light, Swift, Australia). Incremental 1 m markings along the 15 m running track will allow for the calculation of the distances covered during sub-maximal exercise bouts.

**Perceptual Measures:** Participants will be required to provide their reported perceived exertion (RPE) and estimates of thermal stress pre, post and incrementally throughout exercise.

**Blood Sampling:** A capillary blood sample will be drawn from the participant’s earlobe with a sterilised lancet before, during and after each match for the measurement of lactate, pH, and bicarbonate concentrations. Venous blood samples will be collected from a superficial antecubital forearm vein using an evacuated venipuncture system and 7.5 mL serum separator tubes (Monovette, Sarstedt, Numbrecht, Germany) for the measurement of heat stress, cell growth and central fatigue.

**Risks and Discomforts**
A DXA scan during the familiarisation session to determine participant body composition. Radiation exposure from this study is below that of many diagnostic medical x-ray procedures. At these radiation dose levels, no harmful effects have been demonstrated as any effect is too small to measure. The risk is believed to be low and theoretically is approximately equivalent to risk category I - <1:100000.

Participation in all physical activity increases one’s risk of injury. Soft tissue damage may occur, however participation in this study will not significantly increase the risk of injury over and above normal training and competition levels. Trained first aiders will provide assistance where necessary.

Blood collection is likely to be an uncomfortable experience, and all efforts will be directed to ensuring the comfort of the participant during the procedure. Having blood drawn during exercise presents identical risks to other blood collection practices employed in clinical settings. Some participants may experience a small amount of bleeding at the puncture site, though clotting should be complete within 10 minutes. Bruising may occur at the puncture site, but should disappear within 1-2 days.

Throughout assessment of neuromuscular function, an electrical stimulus is applied to the femoral nerve at the inguinal fold. This measure is important for the assessment of central nervous system (CNS) function. Each sensation will last no longer than a couple seconds and the participant should be assured that they are at minimal risk of injury or complication throughout this procedure.

**Data Usage**
It is expected that the data gained from this investigation will be included in a scholarly research article published in an esteemed international sports science journal. Further, results from this investigation will be adopted by Cricket Australia for use with their athletes.

**Confidentiality**
The privacy of all volunteers will be guaranteed and all data acquired from individual participants will be kept strictly confidential. Only the Chief Investigator will have access to participant’s identities.

**Coercion and Withdrawal**
You have the right to participate in this investigation without the intervention of any element of force, fraud, deceit, duress, coercion, or undue influence on your decision. In the event that you agree to participate you have the right to withdraw your consent and cease involvement in the investigation at any time.
Institutional Review Board

Charles Sturt University’s Human Research Ethics Committee has approved this project. I understand that if I have any complaints or concerns about this research I can contact:

Executive Officer  
Human Research Ethics Committee  
Office of Academic Governance  
Charles Sturt University  
Panorama Avenue  
Bathurst NSW 2795  
Tel: (02) 6338 4628  
Fax: (02) 6338 4194

Any issues you raise will be treated in confidence and investigated fully and you will be informed of the outcome.

Thank you for expressing interest in this research. If you agree to participate in this study, please sign the attached consent form.
INFORMATION SHEET

Effects of pre-cooling interventions on intermittent sprint performance in the heat.

Thank you for expressing interest in this research. Please read and retain this information sheet. Should you have any questions regarding this study please do not hesitate to contact:

**Geoffrey Minett** (Principal Investigator)
PhD Student
School of Human Movement Studies
Allen House, N1
Charles Sturt University
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Fax: (02) 6338 4065
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**Background Information**

Major cricket competitions occur in thermally stressful environments placing players at increased risk of heat stress and associated performance and health related decrements. Reducing skin and core temperature via cooling interventions may assist to prevent or alleviate symptoms of exercise- and environment-induced heat stress. Despite physiological and performance based interest in whole- and part-body cooling interventions, the underlying mechanisms remain unknown. Furthermore, the use of laboratory based research with whole-body cold-water immersion strategies reduces practicality for athletes in the field. As a result, research is lacking on the application of small and practical mixed-method techniques in comparison with whole-body cold-water immersion for pre-cooling in the heat. While recent research reports performance improvements for exercise in the heat following pre cooling interventions (Duffield & Marino, 2007), little evidence exists to demonstrate the physiological and performance implications of various mixed-method approaches to attain the greatest ergogenic result.
Purpose
To determine the volume of part-body pre-cooling that is required to elicit physiological and performance responses for use in field environments.

Participant Requirements

Study Design
Participants will be required to be well-trained team sport athletes, currently completing ≥ 2 training sessions and competing on a weekly basis. All testing sessions will be conducted at the Exercise and Sports Science Laboratories (S21). Participants will be required to be in a rested state, maintain a similar dietary pattern and not consume any alcohol 24 h pre-, or caffeine or food in the 3 h pre-testing.

The first testing session will be a familiarisation session to ensure participants are familiar with experimental measures such as the exercise protocol, neuromuscular function, perceptual ratings and cooling interventions. A Dual-Energy X-ray Absorptiometry (DXA) scan will provide analysis of participant body composition. Following this session, all proceeding sessions will be identical, with the pre-cooling intervention the only variable. During these sessions tests of neuromuscular function and blood draws will be included to assess heat shock proteins, cell growth, indicators of central fatigue and anaerobic metabolism.

Pre-Cooling Interventions
Following familiarisation, this investigation will be conducted over 3 data collection sessions. Pre-exercise, participants will be cooled for 15 min with methods involving:

Control: No pre-cooling intervention.
10 min pre-cooling: Mixed-method pre-cooling intervention.
20 min pre-cooling: Mixed-method pre-cooling intervention.

Exercise Protocol
Following resting measures and pre-cooling intervention, participants will perform an intermittent-sprint running protocol comprising of 2 x 35 min identical sessions, separated by a 15 min recovery period. Exercise will occur in controlled environmental conditions of 33°C and 40% relative humidity. The intermittent-sprint running protocol will consist of a series of 6 x 15 m maximal efforts intertwined with 5 min bouts of self-paced activity at prescribed intensities, designed to incorporate the movement requirements for cricket fast bowlers.

Data Collection

Neuromuscular Function: Measures of muscle strength and activation will be attained pre-intervention, pre-exercise, mid-exercise and post-exercise using an endurance muscular voluntary contraction (MVC) protocol with electrical stimulation of the femoral nerve at the inguinal fold. This procedure requires participants to maximally contract their quadriceps muscle against a fixed resistance, to which a short (<0.3 s) electrical stimulus will be applied. This will also occur during maximal contractions, in which the electrical stimulus will be applied at peak force during the contraction.

Body Temperature Core temperature will be measured with a telemetric pill (VitalSense, Mini Mitter, USA), ingested 4 h pre-exercise to ensure passing into the gastrointestinal tract. Participants will be advised that they cannot have an MRI while the pill is in the body until it has been passed and will also be given a bracelet warning as a reminder. Skin temperature will be measured at the sternum, mid-forearm, mid-quadriceps and medial calf via telemetric patches (VitalSense, Mini Mitter, USA). Core temperature and skin temperature will be recorded pre-intervention, post-intervention, pre-exercise and at 5 min increments throughout the exercise protocol via a hand held monitor telemetrically receiving core pill and skin patch measurements. Muscle temperature within the quadriceps (vastus lateralis) will be measured pre-intervention, post-intervention, mid-exercise and post-exercise. Anesthetic skin cream (emla, AstraZenetec, North Ryde, Australia) will be applied around the intended puncture site prior to the insertion of a sterile 22-guage needle and associated thermistor into the muscle belly.
Appendix A

**Exercise Performance:** Exercise performance will be determined via 15 m sprint times and distances covered during sub-maximal exercise bouts. Sprint times will be measured using an infra-red timing system (Speed-Light, Swift, Australia). Incremental 1 m markings along the 15 m running track will allow for the calculation of the distances covered during sub-maximal exercise bouts.

**Perceptual Measures:** Participants will be required to provide their reported perceived exertion (RPE) and estimates of thermal stress pre, post and incrementally throughout exercise.

**Blood Sampling:** A capillary blood sample will be drawn from the participant’s earlobe with a sterilised lancet before, during and after each match for the measurement of lactate, pH, and bicarbonate concentrations. Venous blood samples will be collected from a superficial antecubital forearm vein using an evacuated venipuncture system and 7.5 mL serum separator tubes (Monovette, Sarstedt, Numbrecht, Germany) for the measurement of heat stress, cell growth and central fatigue.

**Risks and Discomforts**
A DXA scan during the familiarisation session to determine participant body composition. Radiation exposure from this study is below that of many diagnostic medical x-ray procedures. At these radiation dose levels, no harmful effects have been demonstrated as any effect is too small to measure. The risk is believed to be low and theoretically is approximately equivalent to risk category I - <1:100000.

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Blood collection is likely to be an uncomfortable experience, and all efforts will be directed to ensuring the comfort of the participant during the procedure. Having blood drawn during exercise presents identical risks to other blood collection practices employed in clinical settings. Some participants may experience a small amount of bleeding at the puncture site, though clotting should be complete within 10 minutes. Bruising may occur at the puncture site, but should disappear within 1-2 days.

Throughout assessment of neuromuscular function, an electrical stimulus is applied to the femoral nerve at the inguinal fold. This measure is important for the assessment of central nervous system (CNS) function. Each sensation will last no longer than a couple seconds and the participant should be assured that they are at minimal risk of injury or complication throughout this procedure.

**Data Usage**
It is expected that the data gained from this investigation will be included in a scholarly research article published in an esteemed international sports science journal. Further, results from this investigation will be adopted by Cricket Australia for use with their athletes.

**Confidentiality**
The privacy of all volunteers will be guaranteed and all data acquired from individual participants will be kept strictly confidential. Only the Chief Investigator will have access to participant’s identities.

**Coercion and Withdrawal**
You have the right to participate in this investigation without the intervention of any element of force, fraud, deceit, duress, coercion, or undue influence on your decision. In the event that you agree to participate you have the right to withdraw your consent and cease involvement in the investigation at any time.
Institutional Review Board

Charles Sturt University’s Human Research Ethics Committee has approved this project. I understand that if I have any complaints or concerns about this research I can contact:

Executive Officer  
Human Research Ethics Committee  
Office of Academic Governance  
Charles Sturt University  
Panorama Avenue  
Bathurst NSW 2795  
Tel: (02) 6338 4628  
Fax: (02) 6338 4194

Any issues you raise will be treated in confidence and investigated fully and you will be informed of the outcome.

Thank you for expressing interest in this research. If you agree to participate in this study, please sign the attached consent form.
INFORMED CONSENT

Effects of pre-cooling interventions on intermittent sprint performance in the heat.

Geoffrey Minett (Principal Investigator)
PhD Student
School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW
2795
Tel: 0437 597 473
Fax: (02) 6338 4065
Email: gminett@csu.edu.au

Dr Rob Duffield (Supervisor)
School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW
2795
Tel: (02) 6338 4939
Fax: (02) 6338 4065
Email: rduffield@csu.edu.au

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School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW
2795
Tel: (02) 6338 4268
Fax: (02) 6338 4065
Email: fmarino@csu.edu.au

I, _________________________________ (print name) consent to participating in the research project titled Effects of pre-cooling interventions on intermittent sprint performance in the heat.

My consent to participate in this research is based on the following terms;

1. The purpose of the research has been explained to me, including the potential risks and discomforts involved.
2. I confirm that I am capable of completing the physical requirements of this research.
3. I have read and understood the information sheet provided to me, and have retained a copy of the information sheet provided to me.
4. I have been given the opportunity to ask questions about the research and received satisfactory responses to all questions I have asked.
5. I am content that I understand what I will be required to do as research participant.
Appendix A

6. I understand that any information or personal details gathered in the course of this research about me are confidential and that neither my name nor any other identifying information will be used or published without my written permission.

7. I understand that I can withdraw my consent at any time before, during, or after testing, without any penalty.

8. I nominate the person below as someone that can be contacted on my behalf in the unlikely event of an emergency:

   Name: ________________________________________________
   Address: ______________________________________________
   Phone: ________________________________________________

9. I am aware Charles Sturt University’s Human Research Ethics Committee has approved this project. I understand that if I have any complaints or concerns about this research I can contact:

   Executive Officer
   Human Research Ethics Committee
   Office of Academic Governance
   Charles Sturt University
   Panorama Avenue
   Bathurst NSW 2795
   Tel: (02) 6338 4628
   Fax: (02) 6338 4194

   Participant signature: _________________________________________
   Date: _______________________________________________________
INFORMATION SHEET

Effects of pre-cooling medium-fast bowling performance in the heat.

Thank you for expressing interest in this research. Please read and retain this information sheet. Should you have any questions regarding this study please do not hesitate to contact:

Geoffrey Minett (Principal Investigator)
PhD Student
School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW
2795

Tel: 0437 597 473
Fax: (02) 6338 4065
Email: gminett@csu.edu.au

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Allen House, N1
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Background Information
Major cricket competitions occur in thermally stressful environments placing players at increased risk of heat stress and associated performance and health related decrements. Reducing skin and core temperature via cooling interventions may assist to prevent or alleviate symptoms of exercise- and environment-induced heat stress. Despite physiological and performance based interest in whole- and part-body cooling interventions, the underlying mechanisms remain unknown. Furthermore, the use of laboratory based research with whole-body cold-water immersion strategies reduces practicality for athletes in the field. As a result, research is lacking on the application of small and practical mixed-method techniques in comparison with whole-body cold-water immersion for pre-cooling in the heat. While recent research reports performance improvements for exercise in the heat following pre cooling interventions (Duffield & Marino, 2007), little evidence exists to demonstrate the physiological and performance implications of various mixed-method approaches to attain the greatest ergogenic result.
**Purpose**
To determine the effects of mixed-method whole-body pre-cooling on physiological and performance responses for cricket fast bowlers.

**Participant Requirements**

**Study Design**
Participants will be required to be well-trained medium-fast bowlers. All testing sessions will be conducted at the Cricket Australia Centre of Excellence (Albion, Brisbane). **Participants will be required to be in a rested state, maintain a similar dietary pattern and not consume any alcohol 24 h pre-, or caffeine or food in the 3 h pre-testing.**

The first testing session will be a familiarisation session to ensure participants are comfortable with experimental measures such as the exercise protocol, neuromuscular function, perceptual ratings and cooling interventions. This session will include assessment of repeat sprint ability and peak bowling speeds. These tests will involve a 6 x 30 m repeat-sprint test to assess participant peak and repeated 30 m running speed. This test will involve 6 repeated maximal 30 m sprint efforts, starting every 30 s. Further, following a bowling specific warm-up, peak bowling speed will be measured using a calibrated radar gun as per Duffield, Carney & Karppinen (2009). Following this session, all proceeding sessions will be identical, with the pre-cooling intervention the only variable. During these sessions tests of neuromuscular function and blood draws will be included to assess heat shock proteins, cell growth, indicators of central fatigue and anaerobic metabolism.

**Pre-Cooling Interventions**
Following familiarisation, this investigation will be conducted over **2 data collection sessions**. Pre-exercise, participants will be **cooled for 20 min** with methods involving: 

**Control:** Participants will complete a 6-over fast bowling protocol in environmental conditions of ≥30°C. No pre-cooling intervention will be administered during this condition.

**Mixed-method whole-body pre-cooling:** Participants will complete a 6-over fast bowling protocol in environmental conditions of ≥30°C following 20 min mixed-method part-body pre-cooling via hand, torso, quadriceps and head. Pre-cooling will be completed with the submersion of hands in ice-water (approximately 10°C), ice-vest, ice-packs to the thighs and cold wet towels over the head, neck and face. Ice-vest and cold wet towels will have been soaking in 3°C ice water prior to application.

**Exercise Protocol**
Participants will perform a 6-over spell of fast bowling with each over separated by self-paced, sub-maximal efforts to incorporate game demands. The players will perform an adaptation of the Cricket Australia-Australian Institute of Sport fast bowling skills test that requires players to bowl a mixture of good length, yorker and bouncer deliveries in a pre-designated order at a grid-based target. Bowling accuracy will be measured by a numerical scale rewarding balls that hit the designated areas with a higher points score. The testing will be performed in pairs, in that while one participant is bowling, the other will undergo simulated fielding activities to impose similar physiological challenges as competition demands.

**Data Collection**

**Neuromuscular Function:** Measures of muscle strength and activation will be attained pre-intervention, pre-exercise and post-exercise using a muscular voluntary contraction (MVC) protocol with electrical stimulation of the femoral nerve at the inguinal fold. This procedure requires participants to maximally contract their quadriceps muscle against a fixed resistance, to which a short (<0.3 s) electrical stimulus will be applied. This will also occur during maximal contractions, in which the electrical stimulus will be applied at peak force during the contraction.

**Body Temperature** Core temperature will be measured with a telemetric pill (VitalSense, Mini Mitter, USA), ingested 4 h pre-exercise to ensure passing into the gastrointestinal tract. Core temperatures will be telemetrically transmitted to a hand held monitor. Participants will be advised that they cannot have an MRI while the pill is in the body until it has been passed and will also be given a bracelet warning as a reminder. Skin temperature will be measured at the sternum, mid-forearm, mid-quadriceps and medial calf via infra-red (ThermoScan, Braun, Germany). Core temperature and skin temperature will be recorded pre-intervention, post-intervention, pre-exercise and at the completion of each over throughout the exercise protocol.

**Exercise Performance:** Bowling performance will be measured throughout the 6-over spell in relation to ball speed and accuracy. Ball speed will be recorded with a calibrated radar gun positioned 10 m behind the bowlers arm and aimed to measure speed upon ball release. Bowling accuracy will be measured with a points-based scoring system developed for the CA-AIS fast bowling skills test. Full and final 5 m run-up
speed will be measured with timing gates (Speed-Light, Swift, Australia). A Global Positioning Satellite (GPS) device harnessed between the superior sections of the scapular will record distance and movement patterns throughout the duration of the testing session.

**Perceptual Measures:** Participants will be required to provide their reported perceived exertion (RPE) and estimates of thermal sensation pre, post and incrementally throughout exercise.

**Blood Sampling:** A capillary blood sample will be drawn from the participant’s earlobe with a sterilised lancet pre- and post-exercise for the measurement of lactate, pH, and bicarbonate concentrations. Venous blood samples will be collected from a superficial antecubital forearm vein using an evacuated venipuncture system and 5 mL serum separator tubes (Monovette, Sarstedt, Numbrecht, Germany) for the measurement of heat stress, cell growth and central fatigue.

**Risks and Discomforts**

Participation in all physical activity increases one’s risk of injury. Soft tissue damage may occur, however participation in this study will not significantly increase the risk of injury over and above normal training and competition levels. Trained first aiders will provide assistance where necessary.

Blood collection is likely to be an uncomfortable experience, and all efforts will be directed to ensuring the comfort of the participant during the procedure. Having blood drawn during exercise presents identical risks to other blood collection practices employed in clinical settings. Some participants may experience a small amount of bleeding at the puncture site, though clotting should be complete within 10 minutes. Bruising may occur at the puncture site, but should disappear within 1-2 days. All blood collection processes will be performed by the lead researcher with qualifications in Pathology Specimen Collection (venipuncture).

Throughout assessment of neuromuscular function, an electrical stimulus is applied to the femoral nerve at the inguinal fold. This measure is important for the assessment of central nervous system (CNS) function. Each sensation will last no longer than a couple seconds and the participant should be assured that they are at minimal risk of injury or complication throughout this procedure.

**Data Usage**

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INFORMED CONSENT

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I, ______________________________________ (print name) consent to participating in the research project titled Effects of pre-cooling interventions on intermittent sprint performance in the heat.

My consent to participate in this research is based on the following terms;

1. The purpose of the research has been explained to me, including the potential risks and discomforts involved.
2. I confirm that I am capable of completing the physical requirements of this research.
3. I have read and understood the information sheet provided to me, and have retained a copy of the information sheet provided to me.
4. I have been given the opportunity to ask questions about the research and received satisfactory responses to all questions I have asked.
5. I am content that I understand what I will be required to do as research participant.
6. I understand that any information or personal details gathered in the course of this research about me are confidential and that neither my name nor any other identifying information will be used or published without my written permission.
7. I understand that I can withdraw my consent at any time before, during, or after testing, without any penalty.
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Name: ________________________________
Address: ______________________________
Phone: ______________________________

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Panorama Avenue
Bathurst NSW 2795
Tel: (02) 6338 4628
Fax: (02) 6338 4194

Participant signature: ________________________________
Date: ________________________________

www.csu.edu.au
INFORMATION SHEET

Effects of post-exercise cooling on recovery following intermittent-sprint activity in the heat.

Thank you for expressing interest in this research. Please read and retain this information sheet. Should you have any questions regarding this study please do not hesitate to contact:

Geoffrey Minett (Principal Investigator)  
PhD Student  
School of Human Movement Studies  
Allen House, N1  
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Panorama Ave  
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Fax: (02) 6338 4065  
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Dr Rob Duffield (Supervisor)  
Senior Lecturer  
School of Human Movement Studies  
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Email: rduffield@csu.edu.au

Background Information
Many major team-sport competitions (Olympic Games, Cricket World Cup, FIFA World Cup) occur in thermally stressful environments placing players at increased risk of heat stress and associated performance and health related decrements. Reducing skin and core temperature via cooling interventions post-exercise may assist to alleviate symptoms of exercise- and environment-induced heat stress. Despite physiological and performance based interest in whole- and part-body cooling interventions, the underlying mechanisms remain unknown. Furthermore, the use of laboratory based research with whole-body cold-water immersion strategies reduces practicality for athletes in the field. As a result, research is lacking on the application of small and practical mixed-method techniques post-exercise in comparison with whole-body cold-water immersion for recovery. While recent research reports enhanced exercise performance recovery following cooling interventions (Smith, 2005; Wilcock, Cronin & Hing, 2006), little evidence exists to demonstrate the physiological and performance implications of various mixed-method approaches or what extent cooling volume may influence mechanistic processes.

Purpose
To compare the effects of practical part-body and mixed-method whole-body cooling techniques with whole-body cold-water immersion.

Participant Requirements
Study Design
Participants will be required to be moderate – well trained team sport athletes, currently completing ≥ 2 sports specific skills and/or conditioning training sessions and competing on a weekly basis. All testing sessions will be conducted at the Exercise and Sports Science Laboratories (S21). Participants will be required to be in a rested state, maintain a similar dietary pattern and not consume any alcohol 24 hours prior to the testing sessions.
The first testing session will be a familiarisation session to ensure participants are familiar with experimental measures such as the exercise protocol, neuromuscular function, perceptual ratings and cooling interventions. Following this session, all proceeding sessions will be identical, with the post-exercise cooling intervention the only variable. During these sessions tests of neuromuscular function and blood draws will be included to assess muscle damage, cell growth, inflammation and anaerobic metabolism.

Pre-Cooling Interventions
Following familiarisation, this investigation will be conducted over 4 data collection sessions. Post-exercise, participants will be cooled for 20 min with methods involving:

- **Control:** No cooling intervention.
- **Mixed-method whole-body cooling:** Cooling the torso, thighs and head, neck and face using an ice-vest, ice-packs and cold, wet towels.
- **Whole-body cooling:** Cooling the whole body via submersion to the neck in a 10°C ice bath.

Exercise Protocol
Following resting measures and pre-cooling intervention, participants will perform an intermittent-sprint running protocol comprising of 2 x 35 min identical sessions, separated by a 15 min recovery period. Exercise will occur in controlled environmental conditions of 33°C and 40% relative humidity. The intermittent-sprint running protocol will consist of a series of 6 x 15 m maximal efforts intertwined with 5 min bouts of self-paced activity at prescribed intensities, designed to incorporate the movement requirements for cricket fast bowlers.

Data Collection

- **Neuromuscular Function:** Measures of muscle strength and activation will be attained pre-intervention, pre-exercise, mid-exercise and post-exercise using an endurance muscular voluntary contraction (MVC) protocol with electrical stimulation of the femoral nerve at the inguinal fold. This procedure requires participants to maximally contract their quadriceps muscle against a fixed resistance, to which a short (<0.3 s) electrical stimulus will be applied. This will also occur during maximal contractions, in which the electrical stimulus will be applied at peak force during the contraction.

- **Body Temperature:** Core temperature will be measured with a telemetric pill (VitalSense, Mini Mitter, USA), ingested 4 h pre-exercise to ensure passing into the gastrointestinal tract. Core temperatures will be telemetrically transmitted to a hand held monitor. Participants will be advised that they cannot have an MRI while the pill is in the body until it has been passed and will also be given a bracelet warning as a reminder. Skin temperature will be measured at the sternum, mid-forearm, mid-quadriceps and medial calf via infra-red (ThermoScan, Braun, Germany). Core temperature and skin temperature will be recorded at rest and at 5 min increments throughout the exercise protocol and cooling intervention period.

- **Exercise Performance:** Exercise performance will be determined via 15 m sprint times and distances covered during sub-maximal exercise bouts. Sprint times will be measured using an infra-red timing system (Speed-Light, Swift, Australia). Incremental 1 m markings along the 15 m running track will allow for the calculation of the distances covered during sub-maximal exercise bouts.

- **Perceptual Measures:** Participants will be required to provide their reported perceived exertion (RPE) and estimates of thermal stress pre, post and incrementally throughout exercise.

- **Blood Sampling:** A capillary blood sample will be drawn from the participant’s earlobe with a sterilised lancet before, during and after each match for the measurement of lactate, pH, and bicarbonate concentrations. Venous blood samples will be collected from a superficial antecubital forearm vein using an evacuated venipuncture system and 5 mL serum separator tubes (Monovette, Sarstedt, Numbrecht, Germany) for the measurement of muscle damage, cell growth and inflammation. All blood-taking processes will be performed by a trained phlebotomist.

Risks and Discomforts
Participation in all physical activity increases one’s risk of injury. Soft tissue damage may occur, however participation in this study will not significantly increase the risk of injury over and above normal training and competition levels. Trained first aiders will provide assistance where necessary.

Blood collection is likely to be an uncomfortable experience, and all efforts will be directed to ensuring the comfort of the participant during the procedure. Having blood drawn during exercise presents identical risks to other blood collection practices employed in clinical settings. Some participants may experience a...
small amount of bleeding at the puncture site, though clotting should be complete within 10 minutes. Bruising may occur at the puncture site, but should disappear within 1-2 days.

Throughout assessment of neuromuscular function, an electrical stimulus is applied to the femoral nerve at the inguinal fold. This measure is important for the assessment of central nervous system (CNS) function. Each sensation will last no longer than a couple seconds and the participant should be assured that they are at minimal risk of injury or complication throughout this procedure.

**Data Usage**

It is expected that the data gained from this investigation will be included in a scholarly research article published in an esteemed international sports science journal. This research is part of a series of cricket related fast-bowling studies supported by a Cricket Australia Sports Science Sports Medicine Research Grant. Accordingly, results from this investigation will be shared with and adopted by Cricket Australia for use with their athletes. Although participants may not be cricket players, the principles explored and insight gained using other team-sport athletes remains applicable within a cricket specific environment. Data presented to Cricket Australia will be in terms of mean ± standard deviation; hence all personal details will be withheld.

**Confidentiality**

The privacy of all volunteers will be guaranteed and all data acquired from individual participants will be kept strictly confidential. Only the Chief Investigator will have access to participant’s identities.

**Coercion and Withdrawal**

You have the right to participate in this investigation without the intervention of any element of force, fraud, deceit, duress, coercion, or undue influence on your decision. In the event that you agree to participate you have the right to withdraw your consent and cease involvement in the investigation at any time.

**Institutional Review Board**

Charles Sturt University’s Human Research Ethics Committee has approved this project. I understand that if I have any complaints or concerns about this research I can contact:

Executive Officer  
Human Research Ethics Committee  
Office of Academic Governance  
Charles Sturt University  
Panorama Avenue  
Bathurst NSW 2795  
Tel: (02) 6338 4628  
Fax: (02) 6338 4194  

Any issues you raise will be treated in confidence and investigated fully and you will be informed of the outcome.

Thank you for expressing interest in this research. If you agree to participate in this study, please sign the attached consent form.
INFORMED CONSENT

Effects of post-exercise cooling on recovery following intermittent-sprint activity in the heat.

Geoffrey Minett (Principal Investigator)
PhD Student
School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW
2795
Tel: 0435 487 903
Fax: (02) 6338 4065
Email: gminett@csu.edu.au

Dr Rob Duffield (Supervisor)
Senior Lecturer
School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW
2795
Tel: (02) 6338 4939
Fax: (02) 6338 4065
Email: rduffield@csu.edu.au

I, ________________________________ (print name) consent to participating in the research project titled: Effects of post-exercise cooling on recovery following intermittent-sprint activity in the heat.

My consent to participate in this research is based on the following terms;

1. The purpose of the research has been explained to me, including the potential risks and discomforts involved.

2. I confirm that I am capable of completing the physical requirements of this research.

3. I have read and understood the information sheet provided to me, and have retained a copy of the information sheet provided to me.

4. I have been given the opportunity to ask questions about the research and received satisfactory responses to all questions I have asked.

5. I am content that I understand what I will be required to do as research participant.

6. I understand that any information or personal details gathered in the course of this research about me are confidential and that neither my name nor any other identifying information will be used or published without my written permission.

7. I understand that I can withdraw my consent at any time before, during, or after testing, without any penalty.

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8. I nominate the person below as someone that can be contacted on my behalf in the unlikely event of an emergency:

Name: ____________________________________________
Address: __________________________________________
Phone: ____________________________________________

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Fax: (02) 6338 4194

Participant signature: _________________________________________
Date: _________________________________________________________
INFORMATION SHEET

Cooling for recovery of fast bowling performance in the heat.

Thank you for expressing interest in this research. Please read and retain this information sheet. Should you have any questions regarding this study please do not hesitate to contact:

**Geoffrey Minett** (Principal Investigator)
PhD Student
School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW
2795
Tel: 0435 487 903
Fax: (02) 6338 4065
Email: gminett@csu.edu.au

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School of Human Movement Studies
Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW
2795
Tel: (02) 6338 4939
Fax: (02) 6338 4065
Email: rduffield@csu.edu.au

**Background Information**
Major cricket competitions occur in thermally stressful environments placing players at increased risk of heat stress and associated performance and health related decrements. Reducing skin and core temperature via cooling interventions may assist to prevent or alleviate symptoms of exercise- and environment-induced heat stress. Despite physiological and performance based interest in whole- and part-body cooling interventions, the underlying mechanisms remain unknown. Furthermore, the use of laboratory based research with whole-body cold-water immersion strategies reduces practicality for athletes in the field. As a result, research is lacking on the application of small and practical mixed-method techniques post-exercise in comparison with whole-body cold-water immersion for exercise recovery. While recent research reports enhanced exercise recovery following cooling interventions (Smith, 2005; Wilcock, Cronin & Hing, 2006), little evidence exists to demonstrate the physiological and performance implications of mixed-method cooling techniques. Further, this study will provide novel information on the effects of cooling for recovery on the sports specific skill set of fast bowlers.

**Purpose**
This study aims to determine the effect of post-exercise cooling on cricket-specific physical and skill performance in the heat. A further aim is to determine the physiological, biochemical and perceptual effect of a field-based, mixed-method whole-body cooling intervention in cricket fast bowlers.

**Participant Requirements**

**Study Design**
Well-trained medium-fast bowlers will be recruited for participation in this study. All testing sessions will be conducted at the Adelaide Oval (North Adelaide, Adelaide). You will be required to be in a rested state, maintain a similar dietary pattern and not consume any alcohol 24 h pre-, or caffeine or food in the 3 h pre-testing.
The first testing session will be a familiarisation session to ensure you are comfortable with experimental measures such as the exercise protocol, muscular function, perceptual ratings and cooling interventions. This session will include assessment of repeat sprint ability and peak bowling speeds. These tests will involve a 6 x 30 m repeat-sprint test to assess participant peak and repeated 30 m running speed. This test will involve 6 repeated maximal 30 m sprint efforts, starting every 30 s. Further, following a bowling specific warm-up, peak bowling speed will be measured using a calibrated radar gun as per Duffield, Carney & Karpinnen (2009). Following this session, all proceeding sessions will be identical, with the cooling intervention the only variable. During these sessions blood draws will be included to assess muscle damage, stress and inflammation.

Cooling Interventions
Following familiarisation, this investigation will be conducted over 2 data collection sessions. Following a 10-over fast bowling protocol in environmental conditions of >30°C, you will be cooled for 20 min with methods involving:

Control: No cooling intervention will be administered during this condition.

Mixed-method whole-body cooling: Cooling will be completed with and ice-vest covering the torso, ice-packs on the quadriceps and hamstrings and cold wet towels over the head, neck and shoulders. Ice-vest and cold wet towels will have been soaking in 3°C ice water prior to application.

Exercise Protocol
For the purpose of this study, you will be required to perform a 10-over spell of fast bowling with each over separated by self-paced, sub-maximal efforts to incorporate game demands. This bowling spell will be an adaptation of the Cricket Australia-Australian Institute of Sport fast bowling skills test that will require you to execute a mixture of good length, yorker and bouncer deliveries in a pre-designated order at a grid-based target. Bowling accuracy will be measured by a numerical scale rewarding balls that hit the designated areas with a higher points score. The testing will be performed in pairs, in that while one participant is bowling, the other will undergo simulated fielding activities to impose similar physiological challenges as competition demands. An additional 4-over spell of fast bowling will be completed 24 h post-exercise as an indicator of cricket specific performance recovery.

Data Collection

Muscle Function: Measures of muscular function will be attained pre-, post-, 1 h post- and 24 h post-exercise using a maximal repeated counter movement jump protocol. Using an infrared optical transmission system (Optojump, Italy), muscular power output, jump height and flight times will be assessed to determined the performance of 10 continuous unweighted counter movement jumps. Jump technique will be standardised throughout, with participants instructed to place their hands on their hips to eliminate arm swing.

Body Temperature Core temperature will be measured with a telemetric pill (VitalSense, Mini Mitter, USA), ingested 4 h pre-exercise to ensure passing into the gastrointestinal tract. Core temperatures will be telemetrically transmitted to a hand held monitor. This pill passes within 24 - 48 hours, though during this time should avoid MRI scans and will be given a bracelet warning as a reminder. Skin temperature will be measured at the sternum, mid-forearm, mid-quadriceps and medial calf via infra-red (ThermoScan, Braun, Germany). Core temperature and skin temperature will be recorded pre-, mid-, post-, 1 h post- and 24 h post-exercise.

Exercise Performance: Bowling performance will be measured in relation to ball speed and accuracy. Ball speed will be recorded with a calibrated radar gun positioned 10 m behind the bowlers arm and aimed to measure speed upon ball release. Bowling accuracy will be measured with a points-based scoring system developed for the CA-AIS fast bowling skills test. Full and final 5 m run-up speed will be measured with timing gates (Speed-Light, Swift, Australia). A Global Positioning Satellite (GPS) device harnessed between the superior sections of the scapular will record distance and movement patterns throughout the duration of the testing session.

Hydration status: Pre-, post-, 1 h post- and 24 h post-exercise measures of nude mass will be recorded using calibrated scales (HW 150 K, A & D, Australia) to estimate body mass changes as a result of sweat loss. Urine Specific Gravity will be assessed pre-exercise as a measure of hydration status.

Heart rates: Heart rates will be measured using a chest transmitter and wrist watch receiver (Polar, Finland) pre-intervention, post intervention, pre-exercise and at 10 min intervals throughout the exercise protocol.

Blood Sampling: Venous blood samples will be collected from a superficial antecubital forearm vein using an evacuated venipuncture system and 5 mL serum separator tubes (Monovette, Sarstedt, Numbrecht, Germany) for the measurement of muscle damage, stress and inflammation.

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Perceptual Measures: Reported perceived exertion (RPE) and estimates of thermal sensation will be recorded pre, post and incrementally throughout exercise. Perceived levels of stress, fatigue, wellness, muscle soreness and sleep quality will be collected following all sessions.

Risks and Discomforts
Participation in all physical activity increases one’s risk of injury. Soft tissue damage may occur, however involvement in this study will not significantly increase the risk of injury over and above normal training and competition levels. Trained first aiders will provide assistance where necessary.

Blood collection is likely to be an uncomfortable experience, and all efforts will be directed to ensuring your comfort during the procedure. Having blood drawn during exercise presents identical risks to other blood collection practices employed in clinical settings. You may experience a small amount of bleeding at the puncture site, though clotting should be complete within 10 minutes. Bruising may occur at the, but should disappear within 1-2 days. All blood collection processes will be performed by the lead researcher with qualifications in Pathology Specimen Collection (venipuncture).

Strenuous exercise in the heat may lead to perceived discomfort and physiological strain above that experienced in thermo-neutral environments. In extreme cases this may lead to dehydration, muscular cramping, nausea and dizziness. However, these risks can be largely reduced with a balanced diet, adequate hydration and fitness levels.

Data Usage
It is expected that the data gained from this investigation will be included in a scholarly research article published in an esteemed international sports science journal. Further, results from this investigation will be adopted by Cricket Australia for use with their athletes.

Confidentiality
The privacy of all volunteers will be guaranteed and all data acquired from individual participants will be kept strictly confidential. Only the Chief Investigator will have access to participant’s identities.

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INFORMED CONSENT

Cooling for recovery of fast bowling performance in the heat.

Geoffrey Minett (Principal Investigator)
PhD Student
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Allen House, N1
Charles Sturt University
Panorama Ave
Bathurst, NSW
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Tel: 0435 487 903
Fax: (02) 6338 4065
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Email: rduffield@csu.edu.au

I, ________________________________ (print name) consent to participating in the research project titled Effects of pre-cooling interventions on intermittent sprint performance in the heat.

My consent to participate in this research is based on the following terms;

1. The purpose of the research has been explained to me, including the potential risks and discomforts involved.

2. I confirm that I am capable of completing the physical requirements of this research.

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Charles Sturt University
Panorama Avenue
Bathurst NSW 2795
Tel: (02) 6338 4628
Fax: (02) 6338 4194

Participant signature: __________________________________________
Date: __________________________________________
Perceptual Scales
Rating of Perceived Exertion (RPE) Scale

0  Nothing at all
0.5  Very, very light
1  Very light
2  Fairly light
3  Moderate
4  Somewhat strong
5  Strong
6
7  Very strong
8
9
10  Extremely strong  (almost maximal)
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Conference Abstracts
Conference Proceedings

2012  Minett, G., Duffield, R., Marino, F., Cannon, J., Billaut, F., & Portus, M.

*Exercise & Sports Science Australia (ESSA) – Gold Coast, Australia*

Cooling for recovery following intermittent-sprint exercise in hot conditions.

2011  Minett, G. M., Duffield, R., Marino, F. E., & Portus, M.

*The Future of Fatigue: Defining the Problem – Bathurst, Australia*

Dosage effects of pre-cooling volume for intermittent-sprint performance in the heat.

2010  Minett, G., Duffield, R., Portus, M., & Kellett, A.

*Conference of Science, Medicine & Coaching in Cricket – Gold Coast, Australia*

Practical, field-based pre-cooling for medium-fast bowling in hot environmental conditions.
Cooling for recovery following intermittent-sprint exercise in hot conditions.

Minett, Geoffrey1, Duffield, Rob1, Marino, Frank1, Cannon, Jack1, Billaut, François2 and Portus, Marc3,4

1 School of Human Movement Studies, Charles Sturt University, Bathurst, AUSTRALIA.
2 School of Sport and Exercise Science, Victoria University, Melbourne, AUSTRALIA.
3 Sport Science Sport Medicine Unit, Cricket Australia Centre of Excellence, Albion, AUSTRALIA.
4 Praxis Sport Science, Paddington, AUSTRALIA.

Correspondence: gminett@csu.edu.au

Introduction
This study aimed to examine the effects of post-exercise cooling interventions on recovery from intermittent-sprint exercise in the heat. A further aim was to compare the effects of practical part-body, mixed-method cooling techniques to traditional cold-water immersion.

Methods
Nine moderate-well trained team-sport athletes (20.9±1.7 yrs; 183.3±7.0 cm; 78.6±7.7 kg) completed two 35-min spells of self-paced intermittent-sprint exercise separated by a 15-min recovery on three separate occasions (32.4±1.0°C, 42.4±6.1% relative humidity). Upon exercise completion, 20-min cooling interventions were administered including a control (CONT; no cooling), mixed-method cooling (MM; iced towel, ice vest and ice packs) and cold-water immersion (CWI; submersion to the suprasternal notch in 9.8±0.4°C cold water). Sprint times and self-paced distances covered were recorded during the exercise protocol. Maximal voluntary contraction (MVC) efforts and central activation ratio (CAR) were recorded pre- and post-exercise, post-intervention, 1-h post- and 24-h post-exercise. Changes in cerebral oxygenation were monitored during all neuromuscular assessments using near-infrared spectroscopy (tissue saturation index: TSI=oxyhaemoglobin [O₂Hb]/total haemoglobin [THb]). Serum creatine kinase, C-reactive protein, testosterone and cortisol concentrations were analysed pre-, post-, 1-h post- and 24-h post-exercise. Heart rate, core and skin temperature were recorded throughout. Statistical analysis was performed using a repeat measure ANOVA to determine differences between conditions. Ethical approval and written informed consent was obtained from all participants before engaging in any testing.

Results
Sprint times and self-paced distances covered did not differ between conditions (P>0.05); nor were any change in physiological, neuromuscular and biochemical variables evident pre- or post-exercise (P>0.05). Both cooling interventions significantly decreased heart rate, core and skin temperature post-intervention and 1-h post-exercise compared to CONT (P<0.05), without differences between MM and CWI (P>0.05). Recovery of MVC was improved with CWI post-intervention and 1-h post-, and 24-h post-exercise (P<0.05), representing an 8.5±7.6% and 13.8±6.4% mean increase during recovery compared to MM and CONT respectively. The CAR was higher post-intervention and 1-h post-exercise (P<0.05) in CWI compared to remaining conditions; however, demonstrated no differences between conditions 24-h post-exercise (P>0.05). Both cooling interventions reduced cerebral [O₂Hb] and [THb] post-intervention (P<0.05), with values remaining lower in CWI trials compared to MM and CONT 1-h post-exercise (P<0.05). Accordingly, the TSI was reduced in CWI compared to MM and CONT post-intervention (P<0.05) and MM cooling 1-h post-exercise (P<0.05). While no significant differences were apparent between conditions in C-reactive protein and testosterone (P>0.05), cortisol and creatine kinase were decreased in CWI compared to CONT at 1-h post- and 24-h post-exercise respectively (P<0.05).

Conclusion/Discussion
These data highlight the dose-specific effects of post-exercise cooling and subsequent influence on recovery following intermittent-sprint exercise in the heat. Importantly, CWI hastened the recovery of neuromuscular function, increasing central activation and easing thermal strain. Despite similar thermoregulatory changes observed between cooling interventions, the larger alterations in cerebral haemodynamics observed during CWI trials may signify a reduced cerebral blood flow and/or increased O₂ consumption by cortical neurones. Regardless, CWI enhanced recovery of voluntary force production and central activation, presenting an effective tool for post-exercise recovery in hot environments for team-sport athletes.
Dosage effects of pre-cooling volume for intermittent-sprint performance in the heat.

Geoffrey M Minett 1, Rob Duffield 1, Frank E Marino 1 and Marc Portus 2,3
1 School of Human Movement Studies, Charles Sturt University, Bathurst
2 Sport Science Sport Medicine Unit, Cricket Australia Centre of Excellence, Brisbane
3 Praxis Sport Science, Brisbane

Correspondence: gminett@csu.edu.au

Purpose: The aim of this study was to determine the effects of pre-cooling volume on neuromuscular function and performance in self-paced intermittent-sprint exercise in the heat.

Methods: Ten male, team-sport athletes (20.9 ± 2.6 yrs; 182.1 ± 8.8 cm; 77.8 ± 6.7 kg) completed two 35-min spells of self-paced intermittent-sprint exercise separated by a 15-min recovery on four separate occasions (33.0 ± 0.7°C, 33.3 ± 3.9% relative humidity). Each session was preceded by a pre-cooling intervention designed to be incrementally greater in surface area coverage but still remain practically manageable in the field. Interventions included a control (CONT; no cooling), head (H; pre-cooling with an iced towel), head and hand (HH; pre-cooling with an iced towel and containers of cold water) and mixed-method whole-body (WB; pre-cooling with iced towel, container of cold water, ice vest and ice packs applied to the quadriceps). Cooling was applied for 20-min pre-exercise and reapplied for 5-min mid-exercise. Performance outcomes were determined according to 15-m sprint times, % decline and self-paced distances covered throughout the protocol. Maximal voluntary contractions (MVC) and voluntary activation were recorded pre- and post-intervention and mid- and post-exercise. Core temperature and skin temperature, heart rate, perceptual exertion and thermal stress were recorded throughout.

Results: While no significant differences were observed between conditions for mean and peak sprint times during the exercise protocol (P= 0.08-0.91; Figure 1), the maintenance of sprint speed is reflected following WB pre-cooling with a reduced % decline (P= 0.04). Overall self-paced distances covered were significantly higher with WB (4833 ± 380 m) and HH pre-cooling (4644 ± 360 m) compared to H (4602 ± 448 m) and CONT conditions (4413 ± 545 m), respectively (P= 0.001-0.04). Mean and total hard running distances increased with WB pre-cooling 8.4 ± 4.5% compared to CONT (P= 0.001), further, WB was 5.3 ± 5.8 and 6.7 ± 3.2% greater than HH (P= 0.02) and H (P= 0.001) pre-cooling, respectively (Figure 1). Despite this increased workload, no significant reductions in pre- to post-exercise MVC were detected following WB and HH pre-cooling (P= 0.43-0.93; Figure 1). Core temperature was reduced by 0.1-0.3°C with WB and HH pre-cooling at the completion of the intervention period compared to remaining conditions (P= 0.003-0.04). Moreover, skin temperature was significantly lowered in WB pre-cooling trials (P= 0.001) and overall heart rate responses were significantly suppressed in comparison with CONT (P<0.001).

Conclusion: These data highlight a dose-response relationship between the pre-cooling volume and ensuing exercise performance gains to correspond with a reduced physiological and thermoregulatory response. While part-body pre-cooling may provide some thermal benefit, cooling a larger surface area prior to self-paced intermittent-sprint exercise in the heat may aid in the preservation of higher exercise intensities. Accordingly, a reduced heat
stress following pre-cooling may assist in the maintenance of MVC, increasing work output and alleviating centrally-mediated down-regulation of exercise intensity in hot conditions.

Figure 1. Mean ± SD A) individual 15 m sprint times, B) individual hard running distances covered (m) and C) mean peak torque (Nm) pre-intervention, post-intervention, mid-exercise and post-exercise for all pre-cooling conditions. * Significant difference compared to pre-intervention values for Head and Head and Hand trials.
Practical, field-based pre-cooling for medium-fast bowling in hot environmental conditions

Geoffrey Minett 1, Rob Duffield 1, Marc Portus 2 and Aaron Kellett 2

1 School of Human Movement Studies, Charles Sturt University, Bathurst
2 Sport Science Sport Medicine Unit, Cricket Australia Centre of Excellence, Brisbane

Correspondence: gminett@csu.edu.au

Introduction: Medium-fast bowling performance places significant strain on all physiological systems (Burnett, Elliot & Marshall, 1995; Duffield, Carney & Karppinen, 2009). When performed in hot conditions, this physiological load may be exacerbated as efficiency of heat transfer to the surrounding environment is reduced. Accordingly, high environmental temperatures and/or humidity may present conditions that are problematic for optimal physical performance. Given the well documented negative effects of hot ambient conditions or high core body temperature on exercise performance, pre-cooling methods to counter these effects have become popular. Whole-body cold water immersion within laboratory settings can improve exercise performance in the heat (Marino, 2002). However this procedure can be logistically difficult in field environments, where access to water, water quality, pre-game routines and the number of players restricts effective implementation. Recent studies report the use of mixed-method pre-cooling utilising multiple, smaller cooling interventions may offer ergogenic properties and greater practicality than cold water immersion (Duffield, Steinbacher & Fairchild, 2009; Quod et al., 2008). Given the ecological validity of these methods, practical interventions may be a viable pre-cooling intervention for both training and competitive environments, without the constraints, difficulties and interruptions of whole-body techniques. Therefore, the current study aimed to investigate the effect of practical pre-exercise cooling methods on performance and physiological responses during a 6-over medium-fast bowling spell in the heat. This evaluated the effects of a practical, mixed-method intervention that is inexpensive, transportable and requires minimal intrusion on pre-game preparation for any cricket team playing or travelling to hot environments.

Methods: Using a randomised, repeated measures cross-over design, ten male (22.9 ± 7.7 yrs; 189.8 ± 8.8 cm; 84.9 ± 12.6 kg) club to state level medium-fast bowlers completed two sessions to examine the effects of a field-based pre-cooling intervention on physiological, perceptual and performance responses during a 6-over medium-fast bowling spell in the heat (32°C, 63%RH, 31°C WBGT). Following resting measures, participants completed either the pre-cooling intervention or control condition. The pre-cooling intervention consisted of 20 min mixed-method cooling. Players wore an ice-vest (Arctic Heat, Brisbane, Australia), along with a cold, wet towel placed over the head and neck and exposed regions of the arms. Additionally, players placed their non-bowling hand in a container of ice-cold water (10°C) and had frozen ice-packs (Techni Ice, Frankston, Australia) placed on each quadriceps muscle. During the control condition, players sat passively in the warm conditions. Subsequently, participants completed a 10 min warm up consisting of jogging, sprints, and 10 deliveries to reach normal bowling speeds. Each session consisted of a 6-over spell, based on the CA-AIS bowling skills test. Bowling in pairs, participants performed simulated fielding activities between overs, including; walking in with the bowler 10 m each ball and performing a 20 m sprint on the 2nd and 4th balls, respectively. Bowling performance was measured via ball speed (Stalker ATS, Applied Concepts, USA) and ball accuracy by the CA-AIS skills test accuracy target system. Run-up speed was measured with an infra-red timing system (Speedlight, Swift, Australia) to determine overall and final 5 m run-up speed. Before and after the spell, peak lower body power was recorded during repeated (10) counter movement jumps (BMS, Fitness Technology, Australia). During the spell, movement distance and velocity of the bowler was recorded by a 1 Hz Global Positioning System (SPI elite, GPSports Systems, Australia). Further, core temperature (Vital Sense, Mini Mitter, USA), skin temperature (ThermoScan 3000, Braun, Germany), nude mass, heart rate (FS1, Polar Electro Oy, Finland) and perceptual measures of exertion (RPE) and thermal stress (TSS) were recorded throughout the
A repeated measures ANOVA (condition x time) was used to determine differences between conditions. Analysis was performed using the Statistical Package for Social Sciences (SPSS v16.0, Chicago, IL). Significance was accepted when P < 0.05. Effect size analysis (ES; Cohen’s d) was used to determine the magnitude of effect of cooling. An ES of d<0.2 was classified as ‘trivial’, 0.2 – 0.4 as ‘small’, 0.5 – 0.8 as ‘moderate’ and >0.8 as a ‘large’ effect.

Results: No significant differences (P=0.12–0.86; d=0.05–0.42) were detected between pre-cooling and control conditions for mean bowling speeds (114.5 ± 7.1 v 114.1 ± 7.2 km.h⁻¹), accuracy (43.1 ± 10.6 v 44.2 ± 12.5 au), run up speeds (19.1 ± 4.1 v 19.3 ± 3.8 km.h⁻¹) and running distances (4336 ± 666 v 4328 ± 707 m). However, a moderate ES (d=0.74) was observed for increased mean peak speeds reached during the between-over sprints in the pre-cooling condition (22.1 ± 2.2 v 20.6 ± 3.3 km.h⁻¹). Further, no significant differences (P=0.40–0.87; d=0.07–0.55) were apparent for CMJ peak power pre- (2971 ± 649 v 2677 ± 853 W) or post-spell (3099 ± 393 v 3082 ± 321 W). No significant difference was recorded for post-over heart rates between conditions (P=0.08–0.52; d=0.13–0.54; Figure 1, A). However, heart rates prior to each over were significantly lower in the pre-cooling condition (P=0.01–0.04; d=0.96–1.74; Figure 1, A). Mean core temperature was significantly suppressed in the pre-cooling condition, with core temperature reduced during the 6-overs in the pre-cooling condition (P=0.03; d=1.46; Figure 1, B). Mean skin temperature was significantly reduced pre-spell in the pre-cooling condition (31.8 ± 0.8 v 33.1 ± 0.8 °C; P=0.00; d=2.19), nevertheless no significant difference in mean skin temperature was apparent following the 6-over spell (32.3 ± 1.2 v 32.5 ± 1.6 °C; P=0.23; d=23). Significant reductions in nude mass were evident in the pre-cooling condition (1.5 ± 0.6 v 1.9 ± 0.4 kg; P=0.01; d=0.34), while no significant differences in pre-spell USG were apparent between conditions (1.016 ± 0.006 v 1.016 ± 0.007; P=0.81, d=0.04). Finally, significant reductions in mean RPE (4.7 ± 0.9 v 5.3 ± 1.1 au; P=0.03; d=0.77) and mean TSS (4.3 ± 0.2 v 5.2 ± 0.6 au; P=0.00; d=3.13) were evident throughout the 6-over bowling spell in the pre-cooling condition.

Figure 1: Mean ± SD A) core temperature and B) heart rate during a 6-over spell of medium-fast bowling in the heat with and without pre-cooling. *Significant difference compared with control (P>0.05). **Large effect size compared with control (d>0.80).
Discussion: This study aimed to determine whether inexpensive, easily portable, cooling techniques could be used in a real-world training or competition environment to assist performance and reduce the physiological effects of bowling in hot environmental conditions. Bowling performance, as measured by accuracy and ball speed, during a 6-over spell in the heat was not substantially altered by pre-cooling. Limited variation was detected in bowling speeds and accuracy between conditions and minimal decline was present throughout the 6-over spell. Further, the absence of change in run up speed corroborates with previous research using 12 over spells in mild environmental conditions (Burnett, Elliot & Marshall, 1995; Duffield, Carney & Karppinen, 2009). Accordingly, these findings add to the limited availability of research on the effects of pre-cooling on sports-specific skill performance (Horny et al., 2007). Whilst running distances and activity patterns were partially standardised due to set bowling run up length, increased peak 20 m running speeds were apparent within pre-cooling trial. This apparent self-selected higher sprint speed during between-over efforts is in agreement with previous laboratory-based pre-cooling research (Booth, Marino & Ward, 1997; Duffield et al., 2010). Accordingly, while the set pace of bowling is not altered by pre-cooling, the lower physiological and perceptual loads during bowling performance may result in increased selected speeds between overs. Consequently, the acute benefits of pre-cooling for fast bowling performance may not be evident in short singular spells; rather it may be possible for increases in intensity of work performed “off the ball” or during fielding between overs.

Despite having negligible effects on acute, single-spell bowling performance, pre-cooling effectively reduced the physiological and thermoregulatory load experienced by the players. Core temperature was not reduced by the cooling intervention; however, the rise in internal thermal load during the warm up and bowling spell was suppressed following pre-cooling. Thus, a pre-cooling intervention prior to a bowling spell blunts the ensuing rise in core temperature, and hypothetically, with repeated exposures during the day may result in protection against excessive increases in core temperature. This maintenance of thermoregulatory balance after pre-cooling allows for an efficient heat transfer gradient, hence observed reductions in body mass changes attributed to evaporative sweat loss during pre-cooling conditions. These effects allow for the maintenance of blood volume, reducing cardiovascular load and related rise in heart rate (Quod, Martin & Laursen, 2006). As such, the observed reduction in pre-over heart rate may represent a reduced physiological stress, faster recovery and confirm the reduced thermoregulatory effects of pre-cooling on medium-fast bowling performance in the heat. Given access and consumption of adequate volumes of fluid may be difficult, especially in extremely hot climates, pre-cooling may reduce sweat rate, limiting the extent of fluid loss and when combined with a hydration strategy, provide some buffer against excessive levels of dehydration. Pre-cooling may allow players to finish the day or session in an improved physiological state than otherwise expected.

Conclusions: Pre-cooling did not substantially influence bowling performance (speed, accuracy or run up speed), however self-selected peak running speeds during non-bowling activities were improved. Further, pre-cooling reduced the physiological and thermoregulatory load of the 6-over spell, as evidenced via reduced core temperature, heart rate and sweat loss. Finally, pre-cooling also reduced the perceptual load of the bowling spell, with lower subjective ratings of RPE and TSS observed in the cooling condition. As such, pre-cooling may have physiological and perceptual benefits for medium-fast bowling during training or competition in hot environments. Given the reduced load and improved physiological state following a single-spell of bowling, it is feasible that performance benefits may become evident as bowling spells become longer or are repeated in hot environmental conditions. Finally, apart from explicit bowling performance improvements, pre-cooling may be used in a protective fashion to blunt the load of performing in hot conditions; ensuring players finish a session and commence recovery in a better physiological/perceptual state.
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References
APPENDIX D

Photographs
Mixed-method pre-cooling volumes as examined in Study 1 (Chapter 3): A Whole-Body; B Head + Hand; C Head; D Control.
A Cricket Australia-Australian Institute of Sport fast-bowling skills test target as utilised in Study 3 (Chapter 5) and Study 5 (Chapter 7); B Mixed-method pre-cooling intervention as examined in Study 3.
Cooling interventions as examined in Study 4 (Chapter 6): **A** Cold-water immersion; **B** Mixed-method cooling; **C** Control.
A Participant executing medium-fast bowling delivery as conducted in Study 5 (Chapter 7);
B Mixed-method post-exercise cooling intervention as examined in Study 5.