University of Alberta

The Effects of Cranial Cooling During Uncompensable Heat Stress in Fire Protective Ensemble

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science

Faculty of Physical Education and Recreation

Spring 2014
Edmonton, Alberta

Abstract

This experiment investigated the physiological effects of cranial cooling during recovery from fully-encapsulated exercise with fire protective ensemble. On two separate days, twelve males completed 2x20 minutes of treadmill exercise (EX1 and EX2) at 65 ± 4 % of VO_{2peak}, each followed by 20 minutes of encapsulated recovery (R1 and R2). During recovery, either active (AC: hood perfused with 10°C water) or passive (PC: head exposed to ambient conditions) conditions were randomly assigned. Core temperature (T_c) increased significantly and by a similar amount from rest to the end of EX2 in both conditions. Both AC and PC conditions led to a similar decrease in core temperature during R1. However, a significant interaction between conditions occurred during R2 ($p = 0.035$) which suggests that AC was more effective than PC at the end of the protocol when core temperature was highest. Despite decreases in T_c during recovery, heat storage was cumulative.

Acknowledgement

To my family, thank you for your patience, constant support and love. I especially must acknowledge the grace of my wife Constance Scarlett and daughter Kassia Scarlett who have brought such joy to my life while sustaining me throughout my studies.

To my supervisory committee members and fellow students, thank you for your keen personalities, hard work and dedication to academic studies.

For the past three years I have been the recipient of exceptional mentorship. Thank you Dr. Stewart Petersen, for your personal guidance and for the outstanding team you have assembled in the work physiology lab. I am one of a succession of fortunate students to begin their careers as a product of this high caliber research group.

A final thanks to all of the research participants without whom this project would not have been possible. Applied physiology requires highly motivated subjects who are also generous with their time. I was fortunate to have recruited a group of volunteers with both of these qualities.

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List of Abbreviations

Abbreviation	**Term**
AC	Active Cranial Cooling
ACD	Active Cooling Device
ANOVA	Analysis of Variance
BP	Blood Pressure
BSA	Body Surface Area
BS	Breathing Stress
ES	Exercise Stress
EX	Exercise Period
FPE	Fire Protective Ensemble
FS	Forearm Submersion
GXT	Graded Exercise Test
HIS	Heat stress index
LCG	Liquid cooling garment
M	Misting
MEP	Maximal expiratory pressure
MIP	Maximal inspiratory pressure
NFPA	National fire protection association
PC	Passive cranial cooling
PSI	Physiological Strain Index
R	Recovery Period
SCBA	Self-Contained Breathing Apparatus
SBC	Selective Brain Cooling
SCG	Short Cooling Garment
TS	Thermal Stress
TSH	Thermal Stress of the Head
TCG	Top Cooling Garment

T_{core}	Core Temperature
ΔT_{core}	Change in Core Temperature
T_i	Intestinal Temperature
T_r	Rectal Temperature
T_e	Esophageal Temperature
UHS	Uncompensable Heat Stress
VT	Ventilatory Threshold
WOB	Work of Breathing

Chapter One

Introduction

1.1 Background

In 24 B.C. Aelius Gallus, the Roman governor in Egypt, led an army into the Arabian deserts. At the time, consuming and topically applying a mixture of olive oil and wine was considered an appropriate cooling method (Jarcho 1967). That army suffered heat stroke, dehydration and death because of an inadequate water supply and the ineffectiveness of their cooling strategy (Jarcho 1967). Humans maintain a core temperature of approximately 37°C, with fatigue and voluntary exhaustion occurring when internal temperature increases as little as 2-3°C (Cheung and Sleivert 2004). Without proper countermeasures an internal temperature in excess of 40°C can lead to heat stroke and death (Glazer 2005; Jardine 2007; Jay and Kenny 2010). Heat stress, fatigue, exhaustion and death are still serious hazards during contemporary work, such as firefighting. Cooling strategies which counteract physiological strain are important to performance and health.

Firefighters are required to suppress fires and attend emergency scenes while wearing a fire protective ensemble (FPE) and a self-contained breathing apparatus (SCBA) (Gledhill and Jamnik 1992). These encapsulating fire protective ensembles offer protection at the cost of increased thermal insulation and decreased vapour permeability (Barr et al. 2010; Cheung et al. 2010; Holmer 2006). The heavily layered FPE creates a saturated microclimate next to the skin. High humidity in the microclimate impairs evaporation, which is the primary method of heat removal during exercise. Impaired whole body evaporation leads to uncompensable heat stress (UHS), which results in heat storage (Cheung et al. 2000; Holmer 2006). The rate of heat storage is increased with exercise intensity, ambient temperature and humidity (Cheung et al. 2000).

Firefighting requires cycling between time on task and recovery (Carter et al. 1999; Schaeffer 2011; Pretorius et al. 2010 Selkirk and McLellan 2005). Using active cooling devices (ACDs) during recovery is a promising countermeasure against heat storage but ACDs are not yet common rehabilitation tools (Barr et al. 2010; Cheung et al. 2010; Selkirk and McLellan 2005). Previously investigated ACDs include forearm submersion in cold water, whole body fanning, low pressure convective hand cooling, cooling vests, and liquid circulating garments (LCGs) (Carter et al. 1999; Giesbrecht et al. 2007; Kim et al. 2011. Several of these countermeasures have also been investigated in combination with each other (Barr et al. 2011) and during live fire drills (Carter et al. 2007; Colburn et al. 2011; Horn et al. 2011). When investigated in laboratory settings ACDs have increased work time and reduced physiological strain when recovery takes place in hot humid conditions, however, recent field studies have questioned the usefulness of ACDs when a moderate recovery environment is available.

During fire operations, time on task is determined by the air supply carried within the SCBA rather than on the effects of heat storage (Cheung et al. 2010; Schaeffer 2011). Thermal hyperpnea, an increase in ventilation proportional to heat storage (White 2006), can result in a more rapid depletion of air (Cheung et al. 2010). Therefore, inadequate cooling may increase the risk of asphyxiation (when a limited air supply is available). Heat exhaustion and asphyxiation are both contributors to on-scene fire-related deaths (FEMA 2010; FEMA 2011; FEMA 2012). The leading cause of on scene mortality, heart attacks, also brings into scope cardiovascular strain which is worsened by the combined effects of exercise, heat storage, and the work of breathing (Butcher et al. 2007; Fahy et al. 2007; Nelson et al. 2009). Enhanced cooling may reduce heat storage, cardiovascular strain and ventilation. These effects would reduce physiological strain and improve air conservation.

1.2. The Purpose and Hypothesis

The purpose of this study was to investigate the effects of cranial cooling during encapsulated recovery and subsequent exercise in FPE. Active cranial cooling (AC) with a liquid cooled hood (water at 10°C) was compared to passive cranial cooling (PC) where the head was exposed to moderate ambient conditions. Thermal, ventilatory, cardiovascular and perceptual responses, as well as maximal voluntary grip strength and inspiratory and expiratory pressures were measured.

Targeting the cranium takes advantage of an accessible region of heat release with persistent blood flow and dense vascularization (Nunneley et al. 1971; Pretorius et al. 2006; Shvartz 1970). It was hypothesized that AC would reduce core temperature, reduce ventilation, lower heart rate and reduce, the perceptual responses to subsequent exercise. Additionally, it was hypothesized that maximal voluntary grip strength and respiratory pressures would be better preserved when AC was used. The advantages of active cooling include improved conduction which takes advantage of the specific heat capacity of water and access to a large thermal gradient for heat loss.

1.3. The Background of Cranial Cooling

Cranial cooling has not been specifically investigated as a recovery strategy for firefighters. The head (cranium, face and neck) is accessible with a minimal removal of protective clothing and a wide range of cooling strategies have demonstrated that the head can dissipate between 30 W and 150 W of energy at rest and during exercise respectively (Pretorius et al. 2006; Rasch et al. 1991; Epstein et al. 1986; Shvartz 1970). The head is heavily vascularized and has a large surface area relative to size (Nunneley et al. 1971). The head is also particularly sensitive to thermal perceptions in hot environments (Arens et al. 2006; Cotter and Taylor 2005).

Head cooling may promote heat loss directly from the brain (Rasch et al. 1991). Air perfused hoods have lowered brain temperature in resting humans (Harris et al. 2008). The cranium, airways, and neck each provide anatomical links to the cerebral circulation. Specifically, proximal cooling of the hypothalamus and stimulation of the trigeminal nerve may contribute both to physiological and perceptual effects (Pretorius et al. 2010; White et al. 2011). Cerebral vasoconstriction also reduces circulation to the brain during moderate exercise in the heat (Nybo et al. 2002). This has been discussed as a possible shielding effect to prevent hot incoming blood from reaching the brain (Zhu et al. 2009). If deep circulatory mechanisms of heat loss are reduced then direct head cooling may provide additional heat release from the brain.

Liquid cooling garments are widely used as cooling devices underneath protective clothing such as bomb disposal suits and spacesuits (Flouris and Cheung 2006; Kim and LaBat 2010). Liquid cooled hoods have been successfully applied in hot dry conditions to stem the rise in core temperature at rest (Epstein et al. 1986) and during moderate exercise (Nunneley et al. 1971; Shvartz 1970) but not with protective clothing (Kim et al. 2011). Liquid cooled hoods have disproportionately affected heat loss, compared to torso cooling, during recovery from light exercise (Nunneley and Maldonado 1983). Hood precooling has also reduced core temperature before, during and after exercise, although this did not improve performance (Palmer et al. 2001).

Different head cooling strategies, including facial cooling and neck cooling have improved exercise tolerance time and time trial performance (Ansley et al. 2008; Schlader et al. 2011; Tyler et al. 2010). Face cooling has also attenuated the rise in core temperature (Simmons et al. 2008). Almost all methods of head cooling have improved comfort or reduced perceived thermal stress and fatigue (Montain et al. 1994; Palmer et al. 2001; Schlader et al. 2011; Tyler et al. 2010).

1.4. The Experimental Design and Protocols

Twenty minutes of exercise at a constant intensity in FPE generated the initial thermal stress. This was followed by a 20 minute recovery period, another 20 minutes of exercise, and finally another 20 minutes of recovery. Active cranial cooling and passive cranial cooling were applied only during recovery periods. Except for the head, each subject remained encapsulated throughout exercise and recovery. The head was exposed to the ambient environment (22.2°C and 5 % R.H.) during passive cooling. The head was covered with the cooling hood during active cooling.

The liquid cooled hood (Allan VanGuard Technologies, Ottawa, ON, Canada) was circulating 10°C water. The hood covered the cranium and distal neck but not the entire neck and face. A compression garment and flash hood were used to ensure a good fit and to insulate cranium to hood heat transfer. Temperature (T_{neck} and T_{core}), heart rate (HR), and blood pressure (BP) were measured during each recovery period. During exercise, T_{neck} and T_{core}, HR, oxygen consumption (VO_2), end tidal carbon dioxide ($P_{ET}CO_2$) and ventilation (V_E) were measured to evaluate the demands of exercise. Immediately after exercise maximal inspiratory and expiratory pressure (MIP, MEP, respectively) as well as grip strength were measured.

The SCBA is known to increase the work of breathing (WOB), especially when minute ventilation rates exceed 70 $L\cdot min^{-1}$ (Butcher et al. 2007). Voluntary maximal inspiratory and expiratory pressures (MIP and MEP, respectively) were measured to evaluate respiratory muscle strength after each period of exercise. Handgrip strength was used to help distinguish between localized fatigue in the respiratory muscles and fatigue resulting from diminished central drive (Morrison et al. 2006).

Eleven-point scales (0-10) were used to characterize exercise stress (ES), breathing stress (BS), and thermal stress (TS, of the body and head only). Each 1 point value was associated with a written visual descriptor. These scales were modified from other sources so that valid descriptors could be used in combination with ordinal level data (Borg 1982; Tikuisis et al. 2002). These scales were validated based on their correlation with concurrently measured physiological data (Table C.14).

A power calculation was done using SigmaPlot® software based on the primary variable of core temperature. The mean detectable difference (0.30°C) and expected standard deviation of residuals (0.20°C) was based on the change in temperature found to be significant with head immersion (Pretorius et al. 2010) and based on other cooling countermeasures (forearm submersion) known to have significant effects (Selkirk et al. 2004). With a sample of 8 subjects and 2 conditions (AC and PC) the power of the ANOVA was projected to be 0.80. To detect a mean difference of 0.25°C with the same variability would require 11 subjects.

1.5. Delimitations

The following dependent variables were selected in order to assess the effects of active and passive cranial cooling.

1. Core temperature (absolute change, relative change and rate of change)
2. Posterior neck skin temperature
3. Estimated heat extraction during active cooling
4. Ventilatory responses (minute and total ventilation, oxygen consumption and the partial pressure of end tidal carbon dioxide.
5. Perceptual responses including exercise stress, thermal stress, thermal stress of the head and breathing stress
6. Maximal inspiratory and expiratory pressures
7. Grip strength
8. Blood pressure
9. Heart rate
10. Physiological strain index
11. Change in body mass

Using the variables listed above, this study was able to measure the effects of active and passive head cooling applied to encapsulated subjects during cyclical work and recovery periods which resulted in UHS.

A convenience sample of males was selected based on familiarity with moderate to hard exercise and previous experience with protective clothing and the SCBA (Table C.1). Therefore, this study was able to describe the effects of exercise and AC or PC recovery when fit males took part in cyclical work, while encapsulated, in temperate ambient conditions.

Exercise intensity was selected based on previous research designed to replicate the metabolic stress of working in FPE (Eves et al. 2003). The resulting aerobic intensity (approximately 30 $\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$) was representative of firefighting (Cheung et al. 2010).

Dehydration occurred during exercise and recovery. Rehydration did not occur until the protocol was finished. These results characterize the shift from a euhydrated to a dehydrated state.

1.6. Limitations

Recovery took place in a cool dry environment (22.2°C, R.H. 5 %). Dry conditions are more favorable to evaporation and hotter conditions can reduce the thermal gradient for convective and conductive heat loss. Because recovery does not always occur in cool dry conditions, active and passive comparisons may be different when the environment does not favour evaporative heat loss.

The duration of recovery was similar to previous research and to the amount of time a firefighter might have after using a full bottle of air (Barr et al. 2011; Giesbrecht et al. 2007). Longer duration recovery or shorter duration recovery could have affected the rate of cooling or total amount of cooling.

A tube lined liquid cooling hood was used (Allan VanGuard Technologies, Ottawa, ON, Canada). The efficacy of this countermeasure was only directly compared to passive cooling. Other cooling countermeasures were not directly compared with the same protocol.

Recovery took place while fully encapsulated. This was a deliberate approach. Remaining encapsulated increased insulation and decreased vapour permeability. The microclimate next to most of the body surface area was hot and humid. This aspect of the experimental design is different than other studies that have sought to maximize all forms of heat loss.

This sample was comprised of young males motivated to complete a challenging protocol of very hard exercise. Because it was a convenience sample there may be limited generalizability to other populations.

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Chapter Two

The Effects of Cranial Cooling During Uncompensable Heat Stress in Fire Protective Ensemble

2.1 Background

Work in fire protective ensembles (FPE) results in heat storage which can reduce time on task and increase the risk of exertional heat illness (Carter et al. 1999; Selkirk et al. 2004). Heat storage increases cardiovascular strain as heart rate must increase to meet the demands of exercise and of thermoregulation (Cheuvront et al. 2010; Gonzalez-Alonso and Calbet 2003).

Active cooling devices (ACDs) are promising countermeasures against heat storage but are not yet common recovery tools (Barr et al. 2010; Cheung et al. 2010; Selkirk and McLellan 2005). Active cooling devices have lowered core temperature and heart rate when recovery takes place in hot and humid environments; however, the need for ACDs has been questioned when the removal of protective clothing is possible and recovery can take place in cool (15-20°C) and dry environments. The development of ACDs remains of utmost practical significance because cool and dry recovery environments cannot be assured and regional cooling may be required when protective clothing cannot be removed.

The effects of cranial cooling during recovery from encapsulated exercise have not been well studied. The head (cranium, neck and face) is accessible with a minimal removal of protective clothing. The head also has profuse vascularization and a large surface area relative to size (Nunneley et al. 1971). A wide range of cooling strategies have demonstrated that the head can dissipate heat (Pretorius et al. 2010; Rasch et al. 1991; Shvartz 1970). The head is also disproportionately sensitive to thermal perceptions in hot environments (Arens et al. 2006; Cotter and Taylor 2005).

Heat storage combined with cardiovascular strain and breathing stress presents a complex physiological challenge. Many firefighter deaths and hospitalizations are attributed to heart attacks, heat illness and asphyxiation each year (Fahy et al. 2007; FEMA 2010; FEMA 2011; FEMA 2012). Cooling countermeasures may reduce all three (Butcher et al. 2007; Carter et al. 1999; Selkirk et al. 2004). Perhaps as considered by Cheung et al. (2010) physiological strain should be evaluated with all three risks in mind.

Thermal hyperpnea, an increase in ventilation proportional to heat storage (White 2006), can result in a more rapid depletion of air when the self-contained breathing apparatus (SCBA) is used (Butcher et al. 2007; Cheung et al. 2010; Schaeffer 2011). Therefore, inadequate cooling may increase air consumption, decrease time on task, and increase the danger of asphyxiation.

The purpose of this study was to investigate the effects of active (AC) and passive (PC) cranial cooling during encapsulated recovery and subsequent exercise in FPE. It was hypothesized that AC would better counteract heat storage thereby reducing thermal, cardiovascular and breathing strain during subsequent exercise.

2.2 Procedures

Prior to participation, all subjects completed informed consent, PARQ+ and physician-directed screening forms. The benefits and risks of all procedures were explained and subjects were reminded of their right to ask questions or withdraw from the study. All protocols and procedures were approved by the appropriate institutional review board.

The study design involved at least four distinct sessions for data collection. The first session was used to complete screening and a graded exercise test (GXT). The second session was used to practice the experimental procedures. The final two sessions were conducted in random order to study the effects of active (AC) or passive (PC) cranial cooling. Subjects not familiar with exercise in FPE at the time of enrolment participated in an additional session prior to the GXT to familiarize them with the FPE.

Five to seven hours before the practice and experimental sessions, a temperature transmitter (Jonah, Vital Sense™, Mini Mitter, Bend, OR) was swallowed. Each subject kept the time of ingestion consistent between trials. Preceding all trials subjects abstained from caffeine and alcohol for 12 hours and vigorous exercise for 24 hours. All four sessions were conducted at the same time of day. Upon arrival a mid-stream urine sample was collected and urine specific gravity was measured using a handheld refractometer (PAL-10S, ATAGO® U.S.A, Bellevue, WA). Next each subject was weighed while wearing shorts of a known mass. Nude mass was determined by subtracting the mass of the shorts. The same procedure was used to determine nude mass at the end of each session. After donning a fire hall uniform subjects were seated and instrumented with a blood pressure cuff on the right arm, a HR monitor around the chest and a temperature sensor on the skin of the posterior of the neck. After 5 minutes of seated rest blood pressure, core temperature and neck temperature were recorded. Subjects proceeded to don their FPE and SCBA. Grip strength, maximal inspiratory and expiratory pressure (MIP and MEP) were measured then mass was measured a second time with the complete protective ensemble.

The graded exercise test took place at a speed of 94 m·min^{-1} (3.5 mph). Subjects breathed from the SCBA while expired gases were analyzed by a metabolic cart (ParvoMedics TrueOne™ 2400 metabolic). While walking, grade increased 2 % every two minutes until ventilatory threshold was clearly identified with the systematic increase of V_E/VO_2 ratio (Wasserman 1987). After VT, grade was increased 2 % every minute until volitional exhaustion (Eves et al. 2002).

The experimental and practice sessions followed the same format. In most cases (8 of 12), following the practice section, the grade of the treadmill had to be decreased 1 to 2 % to ensure that each subject could complete the protocol as close to VT as possible. The entire experimental protocol required just over 100 minutes divided into four 20 minute periods as follows exercise 1

(EX1), recovery 1 (R1), exercise 2 (EX2) and recovery 2 (R2). Before EX1 five minutes of expired gases were analysed while the subject was seated and relaxed. A three minute warm-up and cool-down bookended each exercise period. Following exercise MIP, MEP and grip strength were measured while standing. Recovery took place in the same room, while seated, and still wearing the FPE but not the SCBA. Transitions from one period to the next were timed and took between five and seven minutes.

2.3 Methods

2.3.1 Active and Passive Cranial Cooling Conditions

During active cooling the subject wore a high density tube-lined hood (Allan VanGaurd Technologies, Ottawa, ON, Canada). The hood was made from 50 % Kermel® and 50 % Viscose® fabric and had 4.6 m of Tygon® tubing woven into the interior. Water was circulated to and from an insulated reservoir by 3 metres of insulated hose. A compression garment (Nylon hosiery) was applied to improve fit and a dry flash hood was applied to insulate the head.

During passive cooling recovery was identical, except that the head and neck were exposed to temperate ambient (22.2°C, R.H. 5 %) conditions. During both conditions the rest of the body remained encapsulated.

2.3.2 Heat Extraction and Water Temperature

Water temperature was maintained at 10 ± 0.5°C (inlet) by adding icy slush to an insulated water circulating tank (VERSA COOL 1105653, Med-Eng Systems Inc. Ottawa, ON). Inline thermistors placed 30 cm from the hood measured the inlet and outlet water temperature. The flow rate of water was 320 $\text{ml}\cdot\text{min}^{-1}$. Gross heat extraction was estimated based on the difference between the inlet and outlet temperature, the flow rate and the specific heat capacity and density of water (Wright and Cheung 2006). Pilot trials were conducted with a Styrofoam® head to determine the heat gain from the environment during 20 minutes of cooling. Net heat extraction was calculated by subtracting the heat gain from the environment from the gross heat extraction measured during each trial. The temperature of 10°C was chosen to avoid skin vasoconstriction (Giesbrecht et al. 2007; Kurz et al. 1995).

2.3.3 Fire Protective Ensemble and the Self Contained Breathing Apparatus

National Fire Protection Association (NFPA) standard 1500 compliant clothing was used. There were slight modifications to the FPE to allow access, through a Velcro® sealed flap, to the arm for blood pressure measurements (Mayne et al. 2009). The port remained closed except when the blood pressure cuff was attached to a digital monitor. The mass of the FPE and SCBA was 22.5 ± 0.5 kg. The FPE included: pants; a jacket; a helmet; a face piece (mask); a flash hood; gloves and the SCBA. The SCBA consisted of a positive pressure regulator (Scott E-Z FLO), connected to a Scott pressure-reducing regulator, attached to a Scott 4.5 Air-Pak cylinder (Scott Safety, Monroe, NC, USA). Running shoes were substituted for firefighting boots for the safety and comfort of the subject during exercise on the treadmill (Nelson et al. 2009). Fire rescue uniforms were worn underneath the FPE, consisting of pants and a short sleeve shirt (55 % Fibrous fire retardant fiber, 45 % cotton, Lion Apparel, Dayton, OH).

2.3.4 Respiratory Gas Exchange

Expired gases were collected through the SCBA mask and regulator which was fitted with a Plexiglas® cone over the exhalation ports (Eves et al. 2002). The distal end of the cone was connected by hose to the metabolic measurement cart. Expired gas from the breathing apparatus was continuously sampled and gas exchange variables were averaged every 20 seconds during the GXT and every 60 seconds during the practice and experimental trials. Flow calibration and gas analyzer calibration were performed immediately prior to and verified immediately following each exercise period.

The partial pressure of end tidal carbon dioxide ($P_{ET}CO_2$) was sampled separately by a pump, a CO_2 sensor and an analyzer (AEI technologies Naperville, IL, Model, model R-1 pump, model P-61B sensor and model CD-3A carbon dioxide analyzer). Expired gases were collected adjacent to the respirator exhaust ports through a dry sample line. The percentage of expired CO_2 was observed for each breath and the highest value was recorded as end tidal. Gas analyzer calibration was performed immediately prior to each exercise period. Percentages were subsequently converted to partial pressures (mmHg) based on the dry ambient conditions.

2.3.5 Heart Rate and Blood Pressure

Heart rate was measured using a Polar™ heart rate monitor (FS1 receiver and T-31 transmitter; Polar Electro Canada, Lachine, QC, Canada). Blood pressure was measured with an automated system while the subject remained still and silent (BpTRU™ Vital Signs Monitor BPM-100, Coquitlam, BC).

2.3.6 Body Temperature

Temperature readings were manually recorded from a telemetry receiver (VitalSense™, VSM-100, Mini Mitter, Bend, OR). Core temperature (T_{core}) was measured telemetrically with a Jonah ingestible capsule (VitalSense™, Mini Mitter, Bend, OR). Absolute core temperature was measured every 5 minutes. Change in core temperature was calculated every 5 minutes relative to the absolute core temperature at the start of exercise. Fluid ingestion was restricted during all trials to avoid interference with gastrointestinal temperature. Standardizing the ingestion time provided core temperature data which should be in agreement with rectal temperature or esophageal temperature (O'Brien et al. 1998). Neck skin temperature (T_{neck}) was measured by a dermal patch (VitalSense™, Mini Mitter, Bend, OR) which transmitted to the same receiver.

2.3.7 Perceptual Responses

Four perceptual responses were measured on 11 point scales modified from other sources to produce ordinal level data (Borg 1982; Tikuisis et al. 2002). Perceived thermal stress was measured during all four periods of the protocol. Perceived thermal stress of the head was only measured during recovery. Perceived breathing stress and perceived exercise stress were only measured during exercise. These scales were validated *post hoc* based on their correlation with concurrently measured physiological data (Table C.14).

Perceived exercise and breathing stress (ES and BS) were as follows:
0 = "None at all" 1 = "Very very easy" 2 = "Very easy" 3 = "Easy"
4 = "Somewhat easy" 5 = "Moderate" 6 = "Somewhat hard" 7 = "Hard"
8 = " Very hard 9 = "Very very hard" 10 = "Maximal".

Perceived thermal stress of the body (TS) and of the head (TSH) were as follows: 0 = "Unbearably cold" 1 = "Very very cold" 2 = "Very cold"
3 = "Cold" 4 = "Cool" 5 = "Moderate" 6 = "Warm" 7 = "Hot" 8 = "Very hot"
9 = "Very very hot" 10 = "Unbearably hot".

2.3.8 Strength Measures

Right hand grip strength was measured using a handgrip dynamometer (JAMAR, Sammons Preston Rolyan, Bolingbrook, IL). For consistency the hand was ungloved and dried before each measurement. The mean of the two best results within 2 kg was used.

Maximal inspiratory and expiratory pressures were measured similar to Butcher et al. (2007). The apparatus consisted of a mouthpiece connected to a rigid occluded tube with a small perforation to prevent facial muscle contribution. Pressure was recorded in centimetres of water (cmH_2O) by a positive/negative pressure gauge (Cole Parmer Co, Stratford, CT, USA). Both measurements were made while standing with a quasi-isometric effort. The inspiratory maneuver was always done first and began at residual volume. The expiratory maneuver began at total lung capacity. These measurements took place immediately after measuring handgrip strength and were repeated until the two highest values were within 10 cmH_2O. The mean of these two values was recorded. To keep the transition time consistent no more than 5 attempts were allowed.

2.3.9 Physiological Strain Index (PSI) and Heart Rate Reserve (HRR)

Physiological strain index and % HRR were calculated after pooling the AC and PC data. HRR and PSI were not used to make inferential comparisons between conditions. They were included to describe the overall physiological strain.

Physiological strain index is a 10 point scale weighted equally between body temperature and HR (Moran et al. 1998). The core temperature portion was calculated relative to each individual resting T_{core} and the T_{core} of 39.5°C. The heart rate portion of the PSI was calculated relative to each subject's resting and maximum HR. The use of each individual's known maximum and minimum HR is a slight modification proposed by Tikuisis et al. (2002) to the original formula used by Moran et al. (1998). The fractional contribution of HR to the PSI was calculated to illustrate the balance of thermal and cardiovascular factors over time. Heart rate reserve was expressed as a percentage within the range between each subject's resting and maximum HR (Cunha et al. 2011).

2.3.10 Statistical Analysis

All statistics are displayed as mean ± SD unless otherwise noted. Statistical software (SigmaPlot 12®) was used for all inferential analysis. All significance levels were set *a priori* to $p < 0.05$. A two way (time and cooling condition), repeated measures, analysis of variance (ANOVA) was used to analyze core temperature, change in core temperature, rate of temperature change, neck skin temperature, heart rate, oxygen consumption, ventilation, partial pressure of end tidal carbon dioxide, heat extraction, blood pressure, perceived exercise stress, perceived breathing stress, perceived thermal stress, and perceived thermal stress of the head. One way repeated measure ANOVA tests were used to analyze changes in body mass, baseline measures and transition times. *Post hoc* Bonferroni adjustments were used for comparisons between conditions at individual time points. Pearson correlations were used to identify relationships between change in core temperature, body surface area, absolute VO_2, absolute core temperature and between perceptual measures and physiological responses.

2.3.11 Formulae

Heat Extraction was estimated as follows:

(1) $\text{Hood heat extraction (W)} = (\Delta T \cdot v \cdot dCp)/60$

Where: ΔT (°C) was the difference between inlet and outlet temperatures; v ($ml \cdot min^{-1}$) was the flow rate; d ($g \cdot cm^{-3}$) was the density and Cp ($J \cdot K^{-1} \cdot g^{-1}$) was the specific heat capacity of water (Wright and Cheung 2006). Heart rate reserve (HRR) and % HRR were determined for each subject as follows:

(2) $HRR = HR_{max} - HR_{min}$

(3) $\% HRR = ((HR_1 - HR_{min}) \cdot (HRR)^{-1}) \cdot 100$

HR_{max} was the highest observed HR of each subject, HR_{min} was the lowest observed HR of each subject during baseline measures, HR_1 was a value obtained at some point during the protocol.

Physiological Strain index (PSI) and the fractional contribution of HR (fHR) were determined as follows:

(4) $PSI = 5 \cdot ((T_1 - T_{baseline}) \cdot (39.5 - T_{baseline})^{-1}) + 5 \cdot ((HR_1 - HR_{min}) \cdot (HR_{max} - HR_{min})^{-1})$

(5) $fHR = (5 \cdot (PSI)^{-1}) \cdot ((HR_1 - HR_{min}) \cdot (HR_{max} - HR_{min})^{-1})$

Baseline temperature ($T_{baseline}$) was the core temperature value obtained during baseline measures, T_1 was a core temperature obtained during the protocol, 39.5°C was an arbitrary top end temperature. This value was lower than the ceiling temperature used during this study (40.0°C) but it was maintained in order to keep consistent with previous uses of this scale (Moran et al. 1998; Tikuisis et al. 2002).

2.4 Results

2.4.1 Subject Characteristics

Thirteen healthy male subjects were recruited to this study from the University of Alberta campus and Edmonton region. On two separate attempts, without completing the experimental protocol, one subject reached a core temperature of 40.0°C and the experimental sessions were terminated. The incomplete results from this subject were not included. The remaining twelve subjects were 27.7 ± 5.1 years old, 177.3 ± 6.5 cm tall and weighed 75.78 ± 9.71 kg on the first day of testing. Body surface area was estimated as 1.9 ± 0.1 m^2 (Du Bois and Du Bois 1989). Instrumentation failed to accurately transmit neck temperatures and core temperature, once each, and perceptual responses were not recorded during one trial; therefore, for those analyses n = 11.

Peak oxygen consumption and ventilatory threshold results obtained during the GXT are displayed in Table 2.1. Each subject's $VO_{2\ peak}$ and HR maximum were used to calculate % $VO_{2\ peak}$ and % HRR. During the experimental trials four subjects surpassed the peak HR observed during the GXT and in those cases the highest observed value was used as maximum HR.

Baseline measures were obtained prior to each experimental trial and are displayed in Table 2.2. Each individual's lowest recorded HR was used to calculate % HRR.

2.4.2 Body Mass and Urine Specific Gravity

Body mass (mean ± SD) was not different at the start of AC or PC (AC 75.2 ± 9.8 kg, PC 75.5 ± 10.0 kg, $p = 0.24$). Body mass decreased during both conditions but was not different between conditions (2.2 ± 0.8 kg during AC and by 2.4 ± 0.7 kg during PC, $p = 0.19$) (Table C.3). This was a change in body mass of approximately 3 %. Urine specific gravity, measured at the start of each day met the criterion for normal hydration. The USG was not significantly different between conditions (AC 1.008 ± 0.005, PC 1.011 ± 0.007, $p = 0.19$).

2.4.3 Core Temperature Responses

Core temperature was not significantly different between the active and passive conditions at any point during EX1 or EX2. At the end of EX1, T_{core} was significantly greater than at the start of EX1 ($p < 0.001$) (Figure 2.1, Table 2.3). At the end of EX2 T_{core} was significantly greater than at the end of EX1 ($p < 0.001$). Overall T_{core} increased by 0.9 ± 0.3°C during EX1 and by 0.8 ± 0.3°C during EX2. The total change in core temperature reached 1.6 ± 0.4°C by the end of EX2. The peak ΔT_{core} (1.8 ± 0.5°C) occurred after the final transition to recovery and was significantly greater than ΔT_{core} at the end of R2 ($p < 0.001$).

During exercise there were no differences in the rate of core temperature increase either between conditions ($p = 0.229$) or between EX1 and EX2 ($p = 1.000$). During AC, the rates of temperature were $2.6 \pm 1.0°C \cdot hr^{-1}$ and

2.5 ± 1.1°C·hr^{-1}, during EX1 and EX2, respectively. During PC the rates of temperature change were 2.6 ± 0.9°C·hr^{-1} and 2.6 ± 0.9°C·hr^{-1}, during EX1 and EX2, respectively.

There was no significant difference in T_{core} between AC and PC during R1. Core temperature decreased 0.3 ± 0.3°C during AC and 0.3 ± 0.2°C during PC. At the end of R1 core temperature was not significantly different than the end of EX1 ($p = 1.000$). At the end of R2 core temperature was significantly greater than at the end of R1 ($p < 0.001$) (Figure 2.1, Table 2.3). Core temperature decreased significantly during R2 (AC 0.5 ± 0.3°C and PC 0.3 ± 0.3°C) (Figure 2.1). There was a significant interaction between conditions ($p = 0.036$). *Post hoc* time point comparisons revealed that AC reduced T_{core} more than PC.

Active cranial cooling but not PC, was significantly correlated with absolute core temperature at the start of recovery and change in temperature during recovery. (AC, R1, $r = -0.68$, $p = 0.02$, R2, $r = -0.70$, $p = 0.016$, PC, R1, $r = -0.41$, $p = 0.214$, R2, $r = -0.50$, $p = 0.115$, Figure 2.2).

2.4.4 Neck Skin Temperature

Neck skin temperature increased during the experiment ($p < 0.001$). There were no differences between active and passive conditions at any point during the protocol ($p = 0.813$). Neck skin temperature at the start of the AC was 35.3 ± 0.5°C compared to 35.4 ± 0.7°C at the start of PC. By the end of EX1 neck skin temperature had risen significantly (AC 37.3°C ± 0.8°C, PC 37.0 ± 0.7°C, $p < 0.001$). Neck skin temperature was significantly cooler at the end of EX2 compared to the end of EX1. (AC 36.0 ± 1.0°C, $p < 0.001$, PC 36.1 ± 0.8°C, $p = 0.005$).

At the end of R1, neck skin temperature (AC 35.5 ± 1.0°C, PC 35.5 ± 0.5°C) and R2 (AC 35.6 ± 1.1°C, PC 35.6 ± 0.4°C) was not different than the start of EX1. Table 2.3 shows these results in comparison to the absolute core temperature and also displays the thermal gradient between core and neck skin temperature.

2.4.5 Heat Extraction

Net heat extraction was not different between R1 and R2 (33 ± 6 W vs. 36 ± 7 W, $p = 0.084$). Heat extraction was significantly greater during the first compared to the second ten minutes of R1 (36 ± 5 W vs. 30 ± 7 W, $p < 0.001$) and R2 (39 ± 6 W vs. 33 ± 5 W, $p < 0.001$). There were no significant differences in heat extraction during the last 10 minutes of R1 compared to the last 10 minutes of R2 ($p = 0.070$). It was estimated that 20 minutes of heat extraction resulted in 39 ± 6 kJ and 42 ± 7 kJ of total heat removal during R1 and R2 respectively. As a percentage, 51 % (20 ± 3 kJ) of total heat extraction occurred during the first ten minutes of R1 and 51 % (22 ± 4.3 kJ) of heat extraction occurred during the first ten minutes of R2.

2.4.6 Individual Responses and Correlational Findings

There was no significant relationship between BSA and overall change in temperature with either AC ($r = 0.12$, $p = 0.716$) or PC ($r = 0.06$, $p = 0.846$). There were no significant relationships between absolute VO_2 during exercise and the change in core temperature during exercise (AC, EX1, $r = -0.20$, $p = 0.551$, EX2, $r = -0.04$, $p = 0.917$, PC, EX1, $r = -0.39$, $p = 0.240$, EX2, $r = -0.46$, $p = 0.159$). During both AC and PC there was a significant correlation between the change in core temperature during EX1 and R1 (AC, $r = -0.84$, $p = 0.001$, PC, $r = -0.70$, $p = 0.018$). Change in core temperature during EX2 was not significantly correlated to change in core temperature during R2 during (AC, $r = -0.52$, $p = 0.102$, PC, $r = -0.53$, $p = 0.094$) (Figure 2.4, 2.5, 2.6).

2.4.7 Heart Rate and Heart Rate Reserve (HRR)

Heart rate increased during EX1 and EX2 ($p < 0.001$). There was no difference in HR response between the active and passive conditions at any time including the end of EX1. Mean heart rate was approximately 80 % HRR during EX1 and approximately 92 % HRR during EX2 (Figure 2.7 and 2.8).

Heart rate decreased during R1 (p = 0.008) and R2 (p < 0.001). There was no difference in HR response between the active and passive protocols at the end of either R1 (p = 0.307) or R2 (p = 0.586). During R1 heart rate was approximately 26 % HRR and during R2 heart rate was at approximately 38 % HRR (Figure 2.7 and 2.8).

2.4.8 Physiological Strain Index (PSI)

Physiological strain index increased from 4 ± 0 to 6 ± 1 during EX1 and from 6 ± 1 to 8 ± 1 during EX2. These values indicate ‘moderate’ strain during EX1 but increased from ‘moderate’ to ‘very high’ strain during EX2 (Moran et al. 1998). The fractional contribution of HR dropped during EX1 (90 % to 69 %) and again during EX2 (69 % to 59 %). By contrast physiological strain index remained stable during R1 (4 ± 1 to 3 ± 1, ‘low’) and R2 (6 ± 1 to 5 ± 1, ‘moderate’) and the fractional contribution of HR was similar during R1 (40 % to 39 %) and R2 (36 % to 36 %).

2.4.9 Blood Pressure

During R1 and R2 AC did not significantly change systolic (R1, AC 102 ± 7 mmHg vs. PC 105 ± 11 mmHg) (R2, AC 101 ± 7 mmHg vs. PC 106 ± 10 mmHg) or diastolic blood pressure (R1, AC 65 ± 7mmHg vs. PC 66 ± 7 mmHg) (R2, AC 64 ± 8 mmHg vs. PC 66 ± 9 mmHg) (p > 0.05). Neither systolic nor diastolic blood pressure changed during recovery (p > 0.10). This was consistent with mean arterial pressure which did not change between AC and PC (AC 77 ± 6 mmHg vs. PC 79 ± 8 mmHg, p = 0.086) or from the start to the end of R1 (80 ± 6 mmHg to 77 ± 7 mmHg) or R2 (79 ± 8 mmHg to 78 ± 7 mmHg) (p = 0.20).

2.4.10 Respiratory Gas Exchange

Through EX1 and EX2 relative oxygen consumption was not different between the active and passive cranial cooling conditions (AC 30.0± 2.8 ml·kg^{-1}·min^{-1} vs. PC 30.0 ± 2.8 ml·kg^{-1}·min^{-1}, $p = 0.995$, $n = 12$). Ventilation rates (reported at BTPS) were not different between protocols (AC 69.2 ± 8.9 L·min^{-1} vs. PC 70.8 ± 9.6 L·min^{-1}, $p = 0.291$, $n = 12$) nor was total ventilation (AC 1361 ± 169 L vs. PC 1384 ± 183 L, $p = 0.407$, $n = 12$). The end tidal partial pressure of carbon dioxide likewise did not demonstrate any difference between conditions (AC 34.2 ± 3.8 mmHg vs. PC 34.1 ± 2.9 mmHg, $p = 0.737$, $n = 9$). Incomplete $P_{ET}CO_2$ data was obtained for 3 subjects so only nine subjects were included in that analysis.

During exercise, no differences were observed between AC and PC therefore the open circuit spirometry responses were pooled in Figure 2.9 to better characterize the physiological effects of work during the protocol. All percentage changes were calculated as the difference in values divided by the highest observed value.

Relative oxygen consumption (VO_2) was stable during EX1 and EX2 but slightly higher overall during EX2 compared to EX1 (30.5 ± 2.8 ml·kg^{-1}·min^{-1} vs. 29.6 ± 2.8 ml·kg^{-1}·min^{-1}, $p < 0.001$) (Figure 2.9, Panel A). Relative oxygen consumption increased by approximately 9 % from the start of EX1 to the end of EX2 (28.8 ± 2.7 ml·kg^{-1}·min^{-1} to 31.5 ± 3.0 ml·kg^{-1}·min^{-1} respectively). Work rate as a percentage of VO_{2peak} during EX1 was 64 ± 4 % and during EX2 was 66 ± 4 %.

As seen in Figure 2.9 (Panel A & B), slight increases in VO_2 were in contrast to large increases in ventilation rate during both EX1 and EX2 (Δ 11 L·min^{-1} and Δ 13 L·min^{-1} respectively). At the start of EX2 ventilation quickly returned to the same rate observed at the end of EX1 (70.5 ± 9.2 L·min^{-1} and 68.1 ± 10.6 L·min^{-1} respectively). Ventilation increased from 59.7 ± 7.7 L·min^{-1} to 81.3 ± 11.7 L·min^{-1} over the two exercise periods, a change of 22 L·min^{-1}, or approximately 27 %.

The end tidal partial pressure of carbon dioxide also significantly changed during both EX1 and EX2 (Δ 3.95 mmHg and Δ 3.97 mmHg respectively) (Figure 2.9, Panel C). $P_{ET}CO_2$ decreased from 38.11 ± 3.06 mmHg to 34.17 ± 2.40 mmHg during EX1 and from 34.27 ± 2.66 mmHg to 30.29 ± 1.56 mmHg during EX2. This was a total decrease of approximately 21 %.

Significantly greater air consumption was observed during the second exercise period compared to the first (AC 1443 ± 198 L vs. 1279 ± 148 L, PC 1465 ± 199 L vs. 1303 ± 177 L, $p < 0.001$) (Figure 2.10). During EX2 an additional 163 ± 89 L (11 %) of air was used.

2.4.11 Strength Measures

Grip strength significantly decreased after the first and the second exercise periods. Grip strength was significantly different between the AC and PC conditions after the second exercise period only. (AC, 50 ± 10 kg vs. PC, 51 ± 11 kg, $p < 0.05$). There was no significant change in either MIP or MEP (Table C.11).

2.4.12 Perceptual Responses

Perceived thermal stress was not significantly different between AC and PC at the end of EX1 (AC 7.5 ± 0.9 vs. PC 7.6 ± 0.9, $p = 0.655$) or EX2 (AC 8.0 ± 1.2 vs. PC 8.3 ± 1.1, $p = 1.81$). The ratings were between “Hot (7)” and “Very Hot (8)”. Perceived thermal stress showed a significant interaction between conditions during recovery ($p < 0.001$). At the end of R1 thermal stress was significantly higher during PC (AC 5.8 ± 0.9 vs. PC 6.6 ± 0.8, $p < 0.001$). At the end of R2 the same was true (AC 6.3 ± 0.9 vs. PC 6.7 ± 1.1, $p < 0.001$). These results are between “Warm (6)” and “Hot (7)” (Table C.7).

Thermal stress of the head was significantly different between conditions and as a factor of time. Thermal stress of the head did not significantly change from the start to the end of R1 (AC 3.9 ± 1.0 vs. 3.6 ± 1.0, PC 5.7 ± 0.9 vs.

5.3 ± 1.0, $p > 0.488$). Thermal stress of the head decreased from the start to the end of R2 (AC 4.5 ± 1.1 to 3.6 ± 0.9, PC 6.4 ± 1.2 to 5.6 ± 1.1, $p < 0.02$). At the end of the first recovery TSH was significantly cooler during AC (AC 3.7 ± 0.7 vs. PC 5.5 ± 0.8, $p < 0.001$). At the end of R2 the same comparison yielded a significant result (AC 3.6 ± 0.9 vs. PC 5.6 ± 1.1, $p < 0.001$).These results were between "cold (3)" and "cool (4)" and "neutral(5)" and "warm(6)" (Table C.8).

Breathing stress changed significantly during EX1 and during EX2 but there was no difference between the active and passive conditions. Five minutes into EX1 breathing stress was "moderate (5)" (AC 5.6 ± 0.8, PC 5.3 ± 0.5). By the end of EX1 breathing stress significantly increased ($p < 0.001$) to between "Somewhat hard" and "Hard" (AC 6.6 ± 1.0, PC 6.4 ± 1.1). Five minutes into EX2 breathing stress had returned to "Somewhat hard" and significantly increased ($p < 0.001$) to between "Hard" and "Very hard" after 20 minutes (AC 6.1 ± 0.8 and 7.5 ± 1.0, PC 6.3 ± 1.1 and 7.6 ± 1.6 respectively) (Table C.9).

Exercise stress changed significantly during EX1 and during EX2 but there was no difference between the active and passive protocols. Exercise stress at the end of EX1 was rated as "Hard" (AC 6.9 ± 1.4, PC 6.8 ± 1.1). Five minutes into the second exercise period ES was rated as "Somewhat hard" and significantly increased ($p < 0.001$) to "Very hard" after 20 minutes (AC 6.2 ± 0.8 vs. 7.9 ± 1.2, PC 6.5 ± 1.0 vs. 8.0 ± 1.3) (Table C.10).

2.5 Discussion

This experiment replicated the heat stress and heat storage that would be expected during the cyclical periods of work and recovery in firefighting. Heat storage was evident during EX1 and EX2 (Figure 2.1) where core temperature increased by approximately 0.9°C regardless of condition. The mean absolute temperature at the end of EX2 was 38.7°C (Table 2.3), which is consistent with other laboratory and field studies which combine FPE and exercise (Barr et al. 2011; Hostler et al. 2010; Selkirk et al. 2004).

2.5.1 Active vs. Passive Cranial Cooling

The main finding was a significant interaction in core temperature responses between AC and PC conditions during R2, which suggests that AC was more effective at reducing core temperature than PC when core temperature was high. The heat storage resulting from exercise was cumulative despite significant reductions in T_{core} during both recovery periods.

In Figure 2.1 it can be seen that core temperature decreased by a similar amount (approximately 0.3°C) with PC during both R1 and R2. Active cooling resulted in a decrease of approximately 0.5°C during R2 which is almost a 40 % increase compared with PC or AC during R1. This difference resulted in a significant interaction effect between conditions ($p = 0.035$). At the start of R2, T_{core} was significantly higher than at the start of R1. The relationship between absolute core temperature and the subsequent decrease in core temperature (Figure 2.2) suggests that the effects of AC exceeded those of PC as core temperature increased. Those individuals who had the highest absolute core temperatures tended to have greater heat loss with AC. Subjects who showed little or no change in temperature during AC were likely to have lower absolute core temperatures. The thermal gradient from the core to the environment was always greater when AC was used.

Skin blood flow was not measured; however, thresholds in absolute core temperature can affect skin blood flow and cutaneous vasodilation (Johnson 1974; Wyss et al. 1975; Kenny et al. 1996). After passive or active heat gain skin blood flow remains elevated in proportion to core temperature (Wyss et al. 1975). Skin blood flow is also affected by increases in plasma osmolality (Shibasaki et al. 2007) and the mechanism is likely inhibition of the skin vasodilator response (Johnson 2010). As skin blood flow decreases elevated core temperature can maintain a higher threshold for skin vasodilation (Kenny et al. 1996). Measuring heat extraction, skin blood flow and vasodilation might have helped to explain the correlation between absolute temperature and change in temperature during recovery when AC was used. During the present protocol AC may have benefitted from increased skin blood flow resulting from higher core temperatures and progressive dehydration (a decrease in plasma volume and an increase in blood osmolality). Higher absolute core temperature may also have maintained skin vasodilation, which potentially favoured AC and conductive heat loss during R2 (Table 2.3).

2.5.2 Heat extraction and core temperature reduction during recovery

Nunneley et al. (1971) reported preliminary results of the effects of using a water perfused hood for active head heat extraction during recovery from exercise. Heat extraction remained elevated for up to 15 minutes after 120 minutes of moderate exercise (Nunneley et al. 1971). Although heat extraction decreased during this time the net effect was between 30 kJ and 80 kJ of heat loss (between 35 W and 85 W depending on hood flow rate and water temperature). Heat loss during recovery was significantly greater than what was observed prior to exercise suggesting that head heat release is elevated in the period immediately after exercise. A limitation of these findings is that only one subject's heat loss results were reported.

Heat loss from the head during PC was not measured in the current study. As a point of reference, Rasch et al. (1991) estimated that ten minutes of seated rest resulted in 55 W or 40 kJ of passive heat loss in normothermic subjects prior to exercise. During subsequent cycle ergometry head heat loss increased to as much as 130 W. Rasch et al. (1991) also found a significant correlation between increases in absolute core temperature and increases in heat loss across workloads suggesting that the heat storage rather than exercise intensity was a factor in head heat loss.

Heat extraction during active cooling, in normothermic subjects, was measured by Pretorius et al. (2010) who demonstrated that 30 minutes of head immersion in 17°C water could remove approximately 80 kJ of heat at a rate of

44 W. Pretorius et al. (2010) found that core (esophageal) temperature decreased by 0.3°C during the first 30 minutes. During the present study twenty minutes of AC extracted approximately 40 kJ of heat at a rate of 35 W. During AC there was a mean decrease in core temperature of 0.5°C during R2 (Figure 2.1) suggesting that AC, applied to hyperthermic subjects, can reduce core temperature at three time the rate compared to whole head immersion with normothermic subjects.

Epstein et al. (1986) used a water perfused hood (circulating 12°C water at a flow rate of 0.06 $L \cdot min^{-1}$) to remove heat at a rate of approximately 34 W during passive heating in a hot dry environment (50°C, 20 % RH). Their cooling hood configuration was similar to the configuration used in the present study (10°C water at a flow rate of 0.32 $L \cdot min^{-1}$ and 35 W of heat extraction). Epstein et al. (1986) demonstrated that the cooling hood could stem increases in core (rectal) temperature, but not lower core temperature, compared to a control condition (37.41 ± 0.08°C vs. 37.80 ± 0.04°C). In contrast, the present study has demonstrated AC can reduce core temperature to a greater extent than PC after heat storage has taken place. In the present protocol it is noteworthy that T_{core} was reduced during PC therefore encapsulation with head exposed did not result in additional heat storage. It would be worthwhile to compare the effects of AC to PC if recovery were to take place in the hot and dry conditions (50°C, 20 % R.H.) used by Epstein et al. (1986).

Palmer et al. (2001), using a water-perfused hood, demonstrated that 60 minutes of precooling decreased core temperature (rectal + esophageal/2) by approximately 0.2°C. The difference in core temperature persisted during 45 minutes of subsequent cycling but did not result in any performance improvements. In comparison to the present study 0.2°C is a small decrease in core temperature given 60 minutes of cooling. This may have been due to the normothermic state of the subjects, however, it is also less than half the decrease in core temperature in normothermic subjects demonstrated by

Pretorius et al. (2010). The relatively small decrease in core temperature observed by Palmer et al. (2001) may be explained by regional vasoconstriction. Palmer et al. (2001) used a cold water temperature (1°C) and previous protocols have demonstrated that rapid skin cooling can delay the decrease in core temperature when cooling hoods are used (Nunneley et al. 1971).

The water-perfused hood, used during the present protocol, extracted a similar amount of heat compared to other water-perfused hoods (Epstein et al. 1986). Compared with heat extraction during head immersion and passive head exposure at rest and during exercise the water-perfused hood was capable of extracting a high proportion of total heat (Pretorius et al. 2010; Rasch et al. 1991). The significant heat extraction observed immediately after exercise (particularly during the first 10 minutes) and the relatively brisk reductions in core temperature observed during the present protocol are most consistent with the observations of Nunneley et al. (1971). The results of the present protocol suggests that AC, using a water-perfused hood, is effective at reducing core temperature during recovery from exercise but not at preventing cumulative physiological strain. Heat extraction results and the correlational findings in Figure 2.2 suggest that there may be an advantage to using AC for heat extraction and to reduce core temperature, immediately following exercise, particularly when an individual’s core temperature is high. Whether AC should be preferred to PC under more severe recovery conditions (hot humid or hot dry UHS) has yet to be determined.

Both cranial cooling and forearm submersion (FS) are regional approaches to cooling. Although FS was not investigated during this protocol it is well researched (Barr et al. 2010; Selkirk et al. 2004; DeGroot et al. 2013), and FS shares many similarities to cranial cooling. The head and forearms represent similar proportions of body surface area, the head is 7 % to 9 % (Nunneley et al. (1971) and the forearms are 5 % to 7 % (Giesbrecht et al. 2007). Both the head and forearms are also well perfused during exercise (Nunneley et al. 1971;

Johnson 1974). Selkirk et al. (2004) reported that forearm submersion resulted in 220 W and 260 W of heat extraction during two 20 minute periods of recovery between 50 minute periods of exercise in FPE. Core (rectal) temperature was significantly lowered during both recovery periods (0.35°C and 0.50°C respectively). Subjects were not encapsulated during recovery; however, recovery took place in hot and humid conditions (35°C 50 % R.H.). Giesbrecht et al. (2007) estimated that FS (in 10°C water) resulted in 180 kJ of heat extraction spread over 3 x 20 min periods of recovery compared to only 50 kJ when passive cooling was used. Core (aural) temperature was decreased by 0.9°C when FS was used.

Compared to the present study head cooling was not capable of removing as much heat as estimates of FS but both AC and PC were capable of reducing core temperature by a similar margin to Selkirk et al. (2004) (0.3°C to 0.5°C). The most significant physiological difference between Selkirk et al. (2004) and the present study was that heat storage was cumulative during the present protocol because AC and PC did not prevent the post-exercise overshoot in core temperature (Figure 2.1).

The combination of de-encapsulation and FS helped to prevent cumulative heat storage. This is an important consideration for future research into the effects of active cranial cooling. Cooling countermeasures in combination with de-encapsulation might prevent the overshoot in core temperature and reduce core temperature more rapidly than if only one method is used.

Elevated core temperature is known to reflect elevated brain temperature. Exercise and hyperthermia both stimulate brain metabolism which also increases the need for cephalic heat release (Nybo and Nielsen 2001; Nybo et al. 2002; Querido and Sheel 2007). One effect of hyperthermia is hyperventilation which leads to cerebral vasoconstriction and reduces brain blood flow (Ainslie and Duffin 2009). Cerebral vasoconstriction may partially protect the brain from becoming overheated but over time the result is inadequate heat release from the brain (Nybo et al. 2002; Zhu et al. 2009). The present research showed a decline in $P_{ET}CO_2$ which can be interpreted as a decrease in $PaCO_2$ (Nybo and Nielsen 2001). While % VO_{2peak} was stable, T_{core} increased, ventilation increased and $P_{ET}CO_2$ decreased. This thermal hyperventilation (Figure 2.9) was indicative of thermal hyperpnea (White 2006). Both the increase in ventilation and decrease in $P_{ET}CO_2$ were cumulative (Figure 2.1 and 2.9). A question for future research remains; if cumulative heat storage had been prevented would changes in $P_{ET}CO_2$ and ventilation have been reduced?

The favourable perfusion of the head and the ability to remove a disproportionate amount of heat per unit surface area is unequivocal in the literature (Pretorius et al. 2006; Pretorius et al. 2010; Rasch et al. 1991). Whether hood cooling can remove enough heat to reduce core temperature is less clear, depending on which protocols were used (Epstein et al. 1986; Kim et al. 2011; Nunneley et al. 1971; Nunneley and Maldonado 1983; Palmer et al. 2001). The effects of head cooling seem to depend on the timing of cooling (before or after exercise), the ambient conditions (cool vs. hot and dry vs. humid) and the absolute core temperature of subjects. The present study has demonstrated that both active and passive cranial cooling can lower core temperature in encapsulated subjects while recovering from exercise. Active cranial cooling was more effective when absolute core temperature was highest however there was substantial variability between subjects. The present protocol did not prevent the overshoot in temperature observed after exercise and this had a substantial effect on cumulative heat storage.

2.5.3 Individual Variability in Temperature Responses

Individual variability was apparent in this experiment (Figure 2.3). The inter-individual responses to AC and PC were similar until R2. During R2 the individual rates of heat removal was more consistent when AC was used.

Heat gain during exercise might have influenced subsequent heat loss. Subjects who gained the most heat during EX1 tended to lose the most heat during R1 but other factors appeared to have changed this relationship during EX2 and R2 (Figure 2.6). Heat gain alone may not explain subsequent heat loss during intermittent exercise. Non-thermal factors such as baroreceptor and chemoreceptor mediated thermal regulation have been shown to affect heat loss during recovery (Kenny and Gagnon 2010).

2.5.4 Physiological Strain

Figures 2.8 and 2.9 present the pooled findings of AC and PC during exercise to better describe the cumulative physiological strain.

The aerobic demand (approximately 30 $ml \cdot kg^{-1} \cdot min^{-1}$) was similar to that required during firefighting activities (Cheung et al. 2010). There was a significant difference in oxygen uptake between EX1 and EX2 however, the physiological difference (between 65 % and 67 % of VO_{2peak}) was small. This difference of approximately 1 $ml \cdot kg^{-1} \cdot min^{-1}$ may have been the result of fatigue, or small changes in movement economy (Barr et al. 2011). The observed work rate of 65 to 70 % VO_{2peak} can be classified between moderate and vigorous activity (Garber et al. 2011) which does not account for other observations of cumulative and near maximal physiological strain.

The elevated HR during EX1 and EX2 were attributable to the effects of hyperthermia and exercise. Elevated skin temperatures (Table 2.3) and approximately 3 % reduction in body mass (Table C.3) were indicative of increased skin blood flow and sweat rate, respectively (Cheuvront et al. 2010; Gonzalez-Alonso and Calbet 2003). These thermoregulatory responses normally enhance heat loss but not while encapsulated (Cheung et al. 2000). When heat strain and exercise occur at the same time there is a greater demand on cardiac output (Cheuvront et al. 2010; Gonzalez-Alonso and Calbet 2003). Blood is directed to the exercising muscles and to the skin. Sweating will lead to a reduction in plasma volume and heart rate must increase in order to maintain systemic blood pressure (Cheuvront et al. 2010; Gonzalez-Alonso and Calbet 2003).

Heart rate reserve was calculated for each subject and therefore served as a good indicator of individualized cardiovascular strain. During 40 minutes of treadmill running in temperate ambient conditions, Cunha et al. (2011) observed that % HRR and VO_2 remained within about a 5 % range (VO_2 was between 60 % and 65 % VO_{2peak}, % HRR was between 67 % and 72 %). In contrast during the present study, at a similar metabolic intensity (65 % VO_{2peak}), for a similar duration of exercise (40 min broken into two 20 min periods) % HRR had to increase by more than 20 % (from 70 % to 95 % HRR). The uncoupling of oxygen consumption and HR clearly illustrates the cardiovascular strain with exercise under UHS.

During recovery, the HR response did not always accurately reflect the changes in body temperature. This is most obvious during the transition times where HR decreased rapidly while core temperatures continued to increase. Horn et al. (2011) investigated the physiological recovery from firefighting activities and observed that HR and core temperature took 50 to 80 minutes to fully recover and that because HR dropped much more rapidly it alone should not be used to predict physiological strain. Selkirk and McLellan (2005) made a similar observation when considering the management of heat stress at fire scenes.

Physiological strain index (Figure 2.8) was calculated to quantify the combined cardiovascular and thermal strain (Moran et al. 1998). Physiological strain index remained ‘moderate’ during EX1 but increased to ‘very high’ during EX2. The proportional contributions of HR to the overall PSI score decreased during exercise but remained similar during both recovery periods. The decreased contribution of HR during exercise is easily explained by the continued rise in T_{core} over time. Interestingly, heat storage had a greater effect on PSI during subsequent exercise than it did on subsequent recovery. The use of PSI with repeated work and rest intervals has not been widely researched and warrants further investigation.

During EX2, ventilation was elevated in comparison to EX1 and continued to increase in comparison to the first five minutes of EX2. The ventilatory response was mirrored by an increase in perceived breathing stress. Ventilation rose from 70 $L \cdot min^{-1}$ to 80 $L \cdot min^{-1}$ (end EX1 to end EX2) while breathing stress rose from 6.5 to 7.5. This change in response from “Somewhat hard” to “Hard’ to ‘Very hard” breathing is indicative of dyspnea. The increase in minute ventilation from 70 $L \cdot min^{-1}$ to 80 $L \cdot min^{-1}$ matches the threshold where the WOB is known to increase while using the SCBA (Butcher et al. 2006).

Total ventilation during exercise was not different between the active and passive conditions, However, due to thermal hyperpnea total air consumption was approximately 160 L greater during EX2 (Figure 2.10). This observation has implications for air management while using an SCBA. A limited air supply is more likely to end work than hyperthermia or fatigue (Schaeffer 2011). An increase in ventilation without an increase in work would decrease time on task. The standard “60” min Scott® air cylinders contain approximately 3000 L of compressed air, 160 L of air represents 2 to 3 minutes of work time at ventilation rates between 75 $L \cdot min^{-1}$ and 80 $L \cdot min^{-1}$. The present study demonstrated that there were cumulative effects on ventilation rate and therefore greater air utilization with repeated periods of exercise. This had two implications. Firstly, as in the above example, firefighters should be aware that for the same work they will use air more rapidly with each additional cycle of work and heat storage. Secondly, cooling countermeasures which prevent cumulative heat storage may also prevent increases in ventilation although the present results were not able to demonstrate this.

Maximal expiratory pressures have been previously observed to decline after exercise with the FPE and the SCBA. Eves et al. (2003) demonstrated that MEP decreased after 30 minutes of continuous walking at ventilatory threshold. Butcher et al. (2007) observed a 14 % increase in fatigue index after three periods of stepping exercise at 80 % peak stepping rate. During the last ten minutes of the walking protocol used by Eves et al. (2003), ventilation was approximately 90 $L\cdot min^{-1}$. Ventilation was approximately 105 $L\cdot min^{-1}$ during the final ten minutes of the stepping protocol used by Butcher et al. (2007). Expiratory pressure and the WOB respectively, increased disproportionately when ventilation was above 70 to 80 $L\cdot min^{-1}$. The additional time spent at high ventilation rates may have been the primary cause for fatigue in the expiratory muscles which led to lower MEP.

During the present study, two 20 minute periods of walking at 65 ± 4 % of VO_{2peak} had no effect on MEP. Ventilation rates during the present study were not sustained at rates as high as what was elicited by the protocols of Eves et al. (2003) and Butcher et al. (2007) (Figure 2.9, Panel B). Less time spent at high ventilatory rates and longer recovery periods between EX1 and EX2 may have resulted in less respiratory muscle fatigue.

Maximal voluntary grip strength was used as an indicator of central fatigue and the small but significant decrease (5 %) may be evidence of the effects of hyperthermia on voluntary contractions. Even brief maximal voluntary contractions have been observed to decrease with passive heating and to a similar magnitude in different muscle groups (Todd et al. 2005). After EX1 additional thermal strain did not produce further change in grip strength. The sensitivity of this maximal strength test may not have been sufficient to detect any further decrements in central drive.

There is evidence to support that contractions of longer duration are more sensitive to hyperthermia induced central fatigue (Hargreaves 2008; Morrison et al. 2004; Todd et al. 2005). A limitation of grip, MIP and MEP, as used in the present study, is that each was a measure of peak strength (peak pressure) as opposed to endurance. It would be difficult to adapt MIP and MEP maneuvers into sustained muscular endurance protocols given the obvious interference with breathing. Perhaps a fatigue index protocol with brief repeated timed efforts to failure would be a more sensitive measure of central fatigue while still detecting fatigue of the respiratory muscles. Grip strength was measured as a maximal 2-3 s contraction and perhaps a longer contraction (10 s or greater) would have been more sensitive (Morrison et al. 2004).

The combination of hyperthermia, elevated HR, and hyperventilation could be viewed as additive strain. Heat storage, cardiovascular strain, and dyspnea have each been reviewed as causes of fatigue and exhaustion (Cheung and Sleivert 2004; Cheuvront et al. 2010; Dempsey et al. 2008). Firefighting appears to combine these stresses. Three prevalent causes of on scene mortality among firefighters are heart attacks, heat stroke, and asphyxiation (FEMA 2010; FEMA 2011; FEMA 2012). Cooling countermeasures should be investigated from the perspective of reducing all three (Cheung et al. 2010; Nelson et al. 2009). Future research could examine if cooling countermeasures can reduce heat storage and as such mitigate increases in ventilation. Whether multiple acute reductions to physiological strain can contribute to improved chronic health is also a topic in need of further study.

2.5.5 Perceptual Responses

Active cranial cooling had a significant effect on perceptual responses during recovery (Table C.7, C.8, C.9 and C.10). Thermal stress and thermal stress of the head were both perceived as less stressful during AC. The head felt “cold” or “cool” compared to “neutral” or “warm”, while the body felt “warm” as opposed to “hot” during recovery. Countermeasures which alter the perceptions of physiological strain during UHS have previously been considered from this perspective.

Partial rather than full encapsulation demonstrated that exposing the head, hands and face could increase tolerance time (46 ± 11 min compared to 100 ± 27 min) and final T_{rectal} (38.8 °C compared to 39.1 °C) during 180 minutes of exercise with UHS (Montain et al. 1994). It was noted that exposure of the head, hands and face brought about similar final T_{rectal} compared with unclothed (not encapsulated) subjects exercising, to exhaustion, in UHS. Improved comfort with partial encapsulation was proposed as an explanation for increased tolerance.

During the current protocol perceived thermal stress and thermal stress of the head were both improved by AC but only during recovery. Selkirk et al. (2004) found that misting and forearm submersion both resulted in significant improvements to thermal comfort. Subjects perceived misting favourably and willingly tolerated higher core temperatures at the termination of exercise. Compared to passive cooling, misting also increased work time. Therefore Selkirk et al. (2004), like Montain et al. (1994), speculated that improvements in thermal comfort may have resulted in prolonged exposure to thermal strain.

Topical menthol rub has been used to induce a cooling sensation rather than actual heat extraction. Lee et al. (2012) found that when menthol was applied to the skin underneath FPE, it impaired the skin vasodilatory response to UHS and hastened heat storage. When menthol was applied to the head only, it did not hasten heat storage. Applying menthol to the head did decrease ratings of perceived exertion and ratings of thermal comfort. Lee et al. (2012) concluded that using menthol during exercise in FPE was strongly contraindicated because from a physiological perspective it results in false perceptual effects. False perceptions of thermal comfort could result in the decision to prolong exposure to high physiological strain, increasing the risk of injury due to exhaustion.

Studies have also investigated the use of heat stress indexes which incorporate perceptual feedback (Petruzzello et al. 2009; Tikuisis et al. 2002). Operationally these would be easily administered and could be used in conjunction with existing markers of physiological strain. These psychological indexes do correlate well with physiological indexes in laboratory compared to field settings (Petruzzello et al. 2009), however research has revealed that they may not be equally representative amongst trained and untrained people (Tikuisis et al. 2002). False perceptions of cooling during UHS may invalidate the potential of these scales although this is a topic which has yet to be studied.

2.5.6 Conclusions

The primary finding of this experiment was that AC was more effective than PC during R2. Cranial cooling during recovery significantly lowered core temperature however, the decrease in core temperature did not prevent cumulative heat storage. Active and passive cranial cooling had similar effects early in the protocol and different effects latter in the protocol. Correlational analysis of individual responses indicated that this may have been a result of higher absolute core temperatures at the start of R2 compared to R1.

There is no doubt that physiological strain increases because of UHS. Design of effective and practical countermeasures to mitigate heat storage remains an important topic for future research. Opportunities for future research with cooling hoods should address the effects in hot humid environments where passive cooling is less effective.

Table 2.1. Mean (± SD) measurements of oxygen consumption (VO_2), heart rate (HR) and grade at peak VO_2 and at ventilatory threshold (VT) during a graded exercise test in fire protective ensemble and SCBA (n = 12).

	VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	VO_2 ($L \cdot min^{-1}$)	HR (bpm)	% $VO_{2\ peak}$ (%)	Grade (%)
$VO_{2\ peak}$	46.2 ± 4.3	3.50 ± 0.50	185.1 ± 10.7	100	17.0 ± 2.6
VT	31.8 ± 3.1	2.39 ± 0.25	155.3 ± 13.8	69.0 ± 5.9	7.6 ± 1.7

Table 2.2. Mean (± SD) baseline core temperature (T_{core}), neck skin temperature (T_{neck}), heart rate (HR), systolic (SYS), diastolic (DIA) and mean arterial pressure (MAP), after five minutes of seated rest in pants and shirt (n = 12).

	T_{core} [a] (°C)	T_{neck} [a] (°C)	SYS (mmHg)	DIA (mmHg)	MAP [b] (mmHg)	HR (bpm)
Active	37.0 ± 0.3	32.5 ± 1.1	103 ± 9	63 ± 11	76 ± 9	64.6 ± 11.7
Passive	37.0 ± 0.2	32.4 ± 1.4	104 ± 8	66 ± 8	78 ± 7	66.0 ± 10.5
p value	0.91	0.74	0.93	0.39	0.27	0.60

[a] n = 11; [b] MAP = DIA + 1/3·(SYS - DIA)

Table 2.3. Mean (± SD) absolute core temperature (T_{core}), neck skin temperature (T_{neck}) and thermal gradient of the neck (TGN) at the end of each exercise and recovery period (n = 11).

	EX1 (°C)	R1 (°C)	EX2 (°C)	R2 (°C)
T_{core}				
Active	37.9 ± 0.4 $^{Y, X, W}$	37.9 ± 0.3 $^{X, W}$	38.7 ± 0.4 $^{Z, Y,}$	38.4 ± 0.3 $^{Z, Y}$
Passive	38.0 ± 0.4 $^{Y, X, W}$	37.9 ± 0.4 $^{X, W}$	38.7 ± 0.5 $^{Z, Y,}$	38.7 ± 0.5 $^{Z, Y}$
p-value	0.366	0.642	0.410	0.037
T_{neck}				
Active	37.3 ± 0.8 $^{Y, X, W}$	35.5 ± 1.0 ^{Z}	36.0 ± 0.9 ^{Z}	35.6 ± 1.1 ^{Z}
Passive	37.0 ± 0.7 $^{Y, X, W}$	35.5 ± 0.5 ^{Z}	36.1 ± 0.8 ^{Z}	35.6 ± 0.4 ^{Z}
p-value	0.175	0.988	0.713	0.981
TGN ($T_{core} - T_{neck}$)				
Active	0.6	2.5	2.7	2.8
Passive	1.0	2.5	2.7	3.1

^{Z} denotes significantly different than EX1. ^{Y} denotes significantly different than R1. ^{X} denotes significantly different than EX2. ^{W} denotes significantly different than R2, $p < 0.001$.

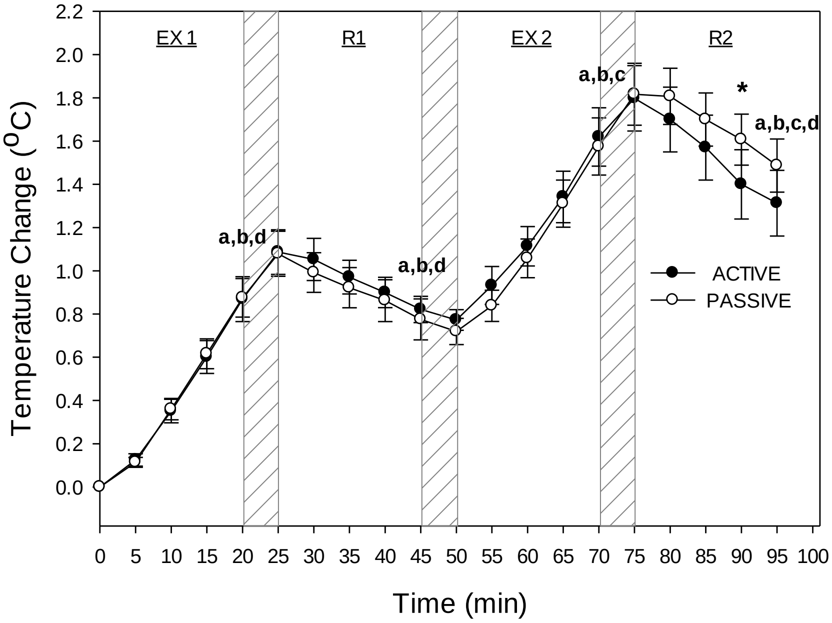

Figure 2.1. Change in core temperature (ΔT_{core}) (mean ± SE) from the first minute of the first exercise period. Shaded bars represent the transitions between exercise (EX) and recovery (R) periods which were approximately five minutes in duration. (* denotes significantly different than ACTIVE $p < 0.05$; ‘**a**’ denotes significantly different than ΔT_{core} at 0 min; ‘**b**’ denotes significantly different than ΔT_{core} at 25 min; ‘**c**’ denotes significantly different than ΔT_{core} at 50 min; ‘**d**’ denotes significantly different than ΔT_{core} at 75 min, $p < 0.001$, $n = 11$). Note: a horizontal comparison reveals that the overshoot in core temperature following exercise was equal to the cooling accomplished during recovery.

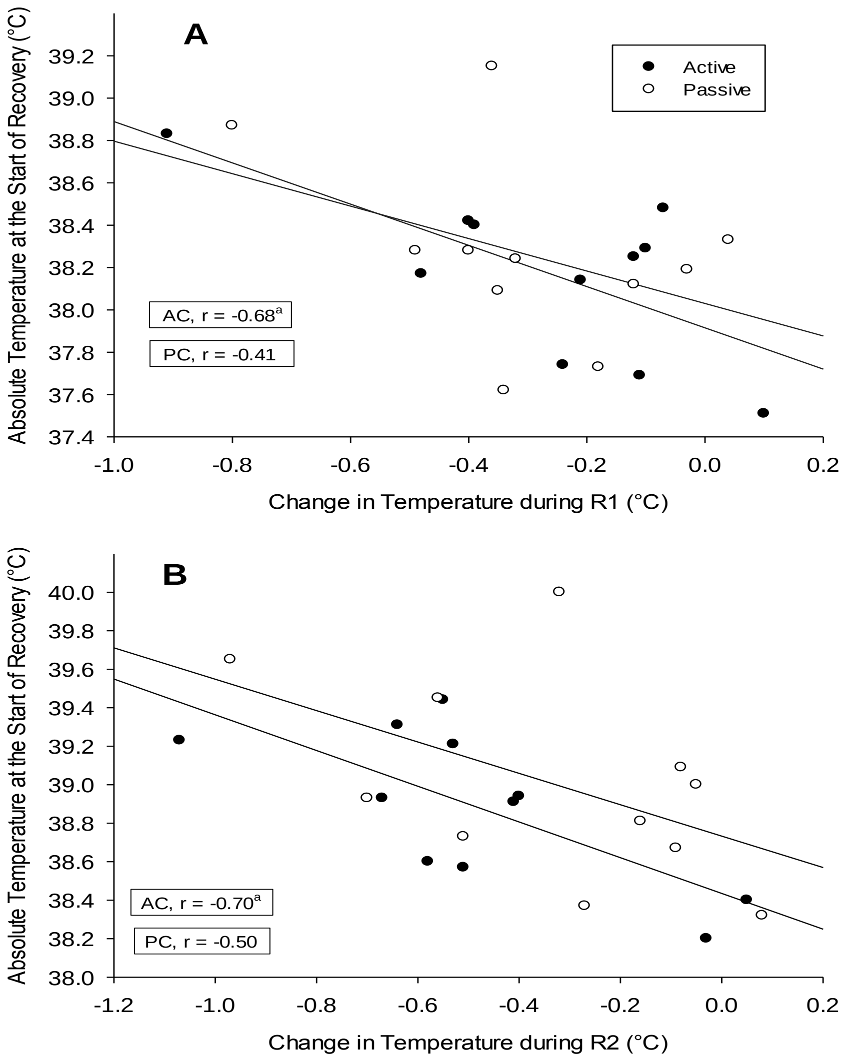

Figure 2.2. The relationship between absolute core temperature at the start of recovery and the change in core temperature measured during subsequent recovery. Panel A displays the active and passive conditions during the first recovery period (R1). Panel B displays both conditions during the second recovery (R2) period. ('**a**' denotes a significant difference, $p < 0.05$, $n = 11$).

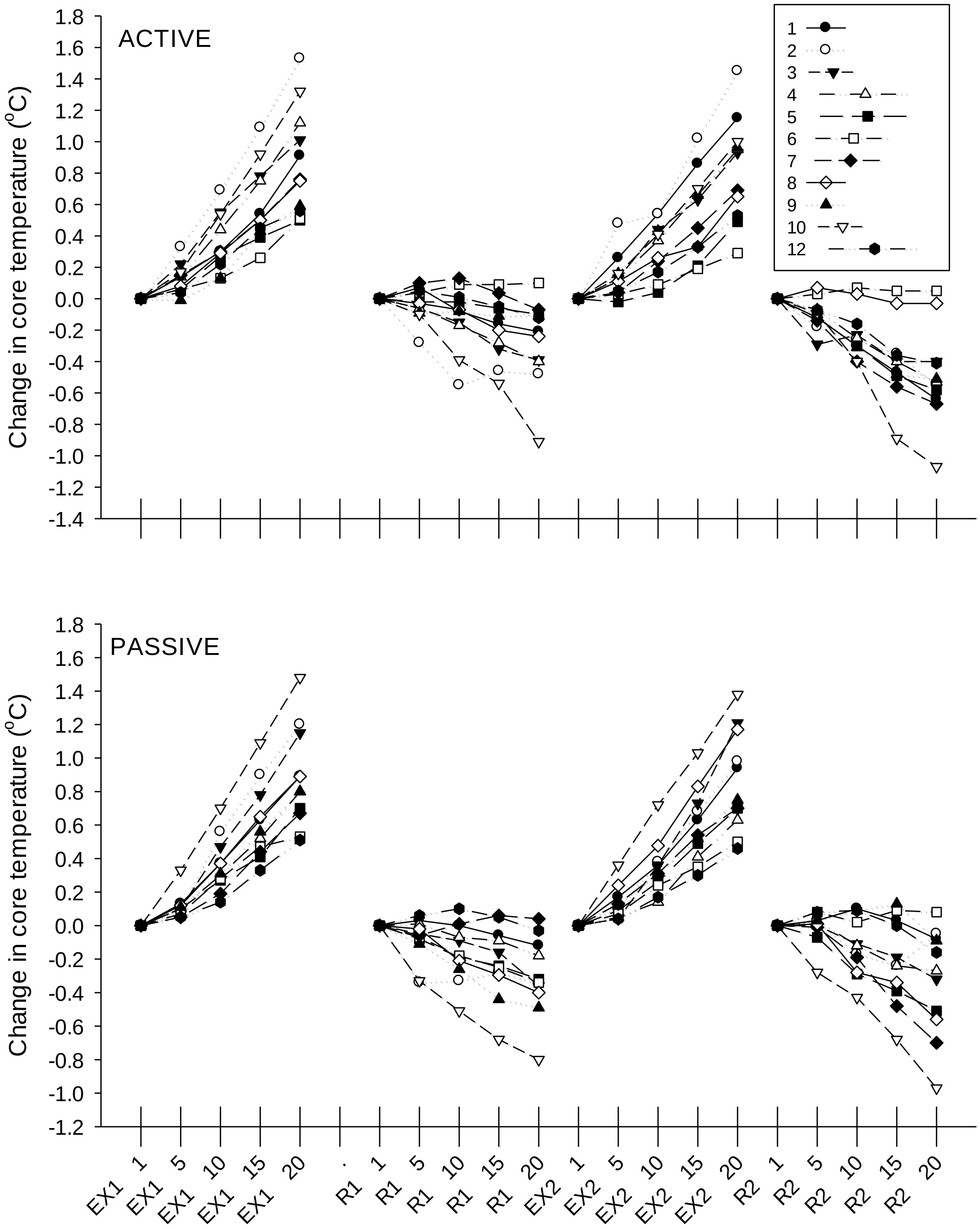

Figure 2.3. The individual changes in core temperature (ΔT_{core}) relative to the first minute of each period. From left to right, each 20 minute period is presented in the order it occurred (EX1 = exercise 1, R1 = recovery 1, EX2 = exercise 2, R2 = recovery 2).

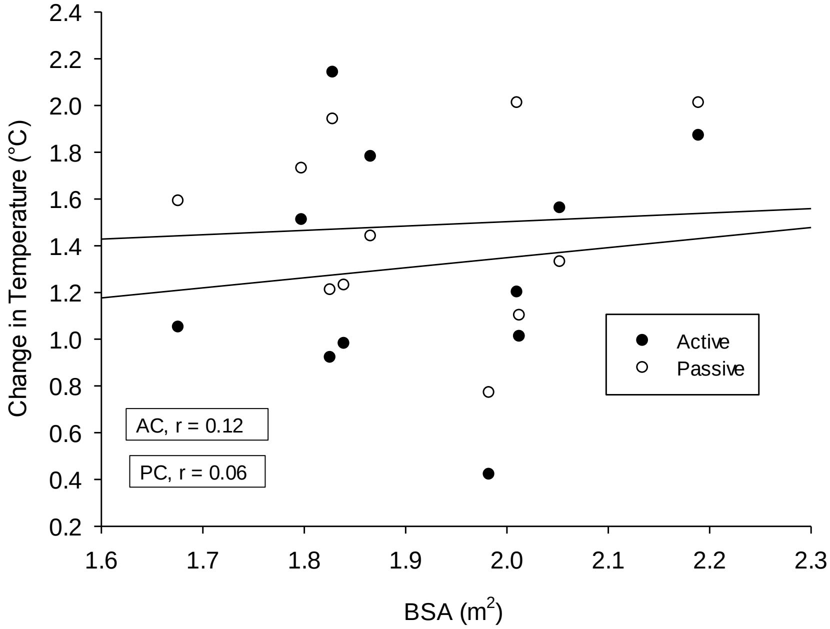

Figure 2.4. The relationship of body surface area to the change in core temperature at the end of the experiment.

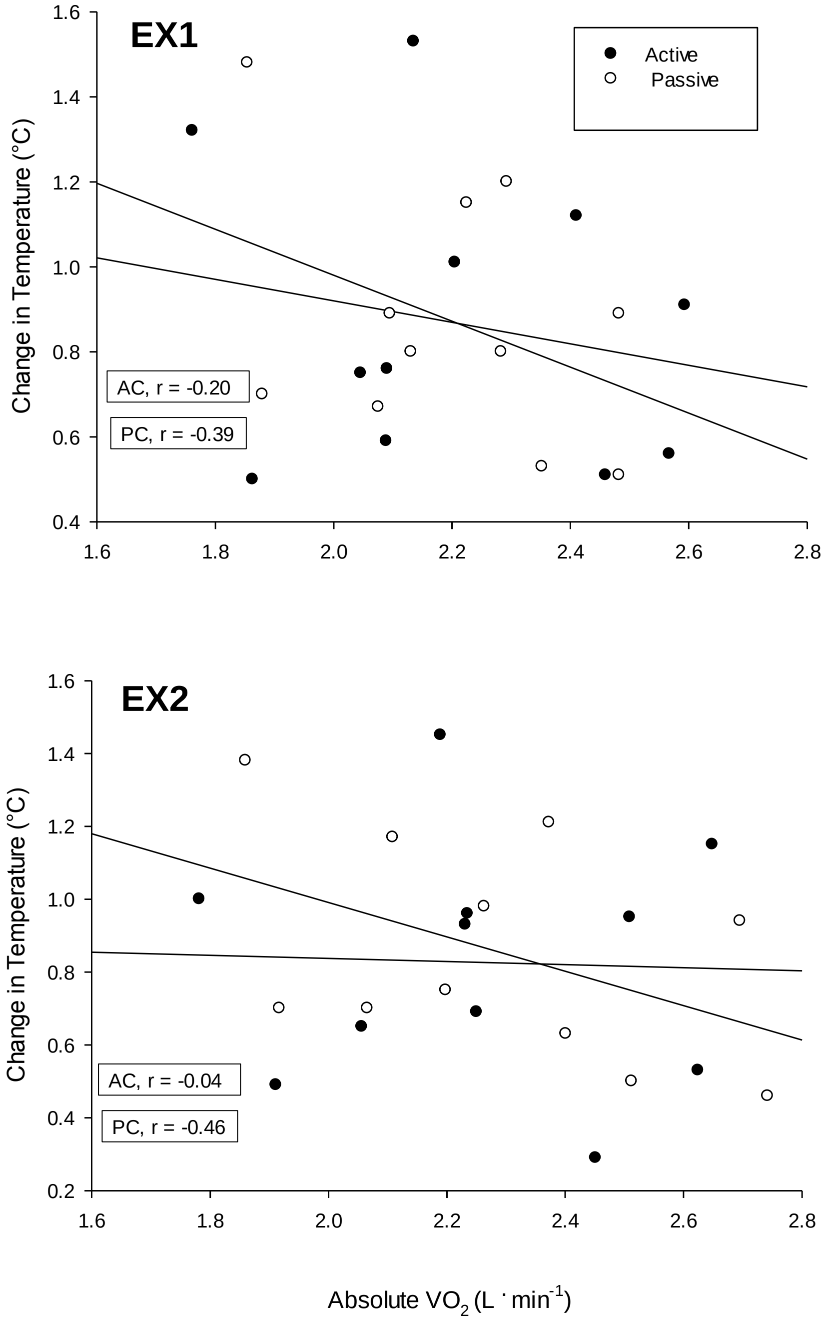

Figure 2.5. The relationship of absolute oxygen consumption to the change in core temperature while exercising. The top Panel displays the active and passive conditions during the first exercise period (EX1) and the bottom Panel displays both conditions during the second exercise period (EX2).

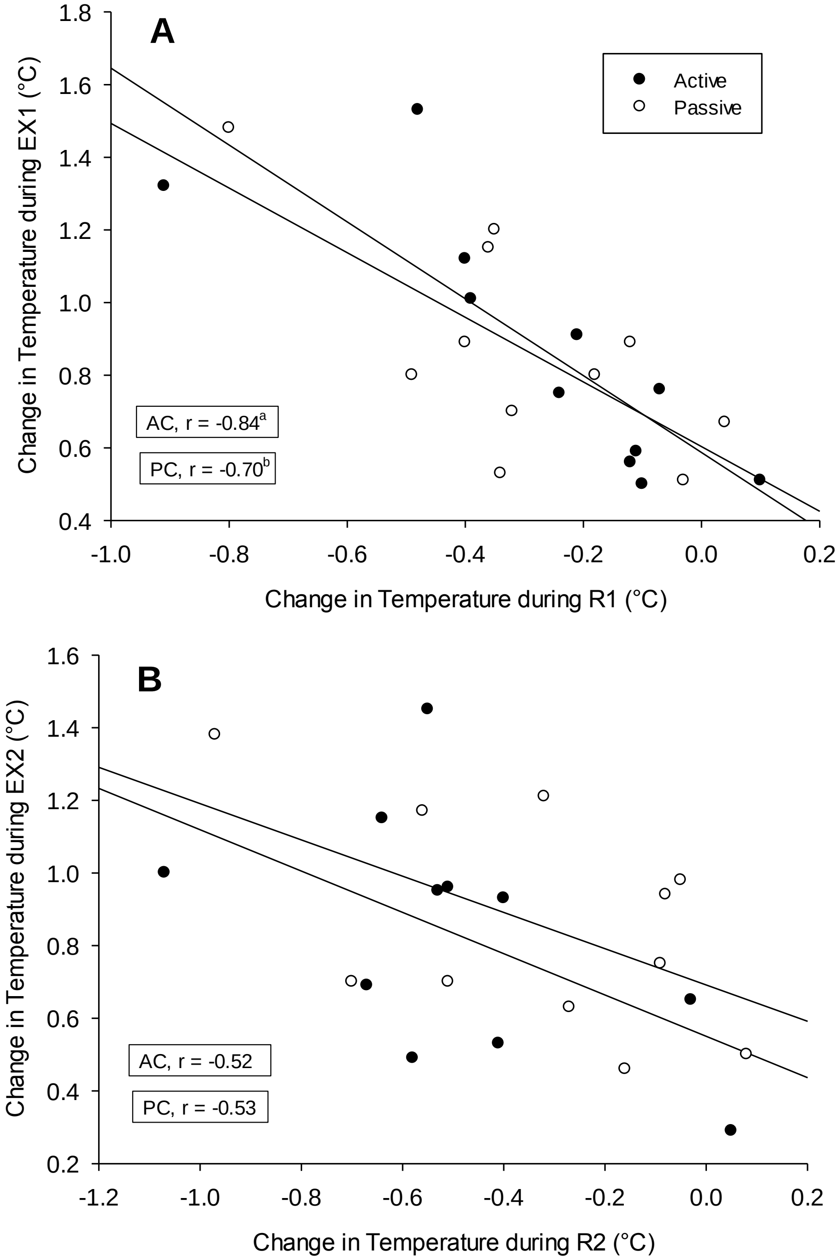

Figure 2.6. The relationship of change in core temperature during exercise to the change in core temperature measured during subsequent recovery. The top Panel A displays the active and passive conditions during the first exercise (EX1) and recovery periods (R1). The bottom B Panel displays both conditions during the second exercise (EX2) and recovery (R2) periods. (‘**a**’ denotes a significant difference, $p < 0.001$; ‘**b’** denotes a significant difference, $p < 0.05$, n = 11).

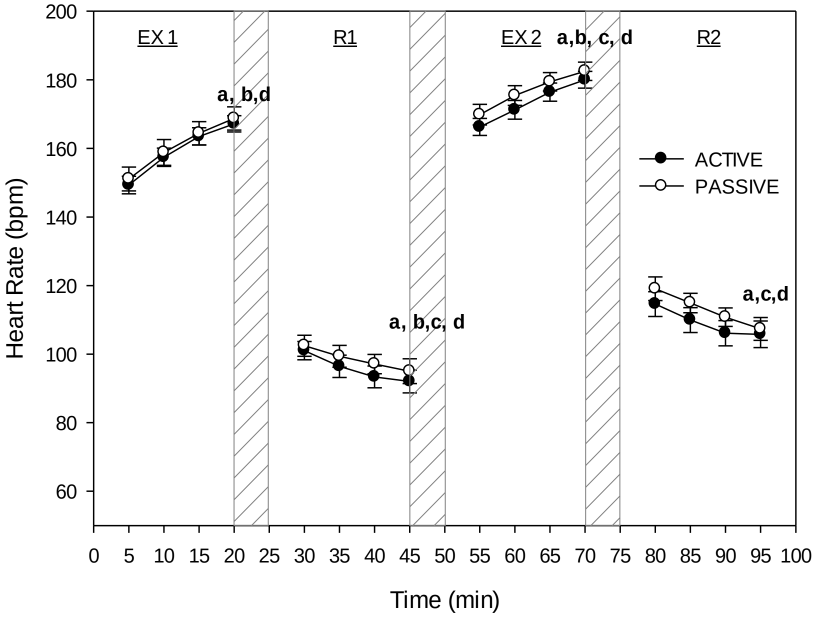

Figure 2.7. Heart rate (mean ± SE) measured during the active and passive protocols. Shaded bars represent the transitions between exercise (EX) and recovery (R) periods which were approximately five minutes in duration. The gap following transitions were excluded to allow HR to adjust to the onset of each period of exercise and recovery (‘**a**’ denotes significantly different than HR at 5 min; ‘**b**’ denotes significantly different than HR at 30 min; ‘**c**’ denotes significantly different than HR at 55 min; ‘**d**’ denotes significantly different than HR at 80 min ($p < 0.001$).

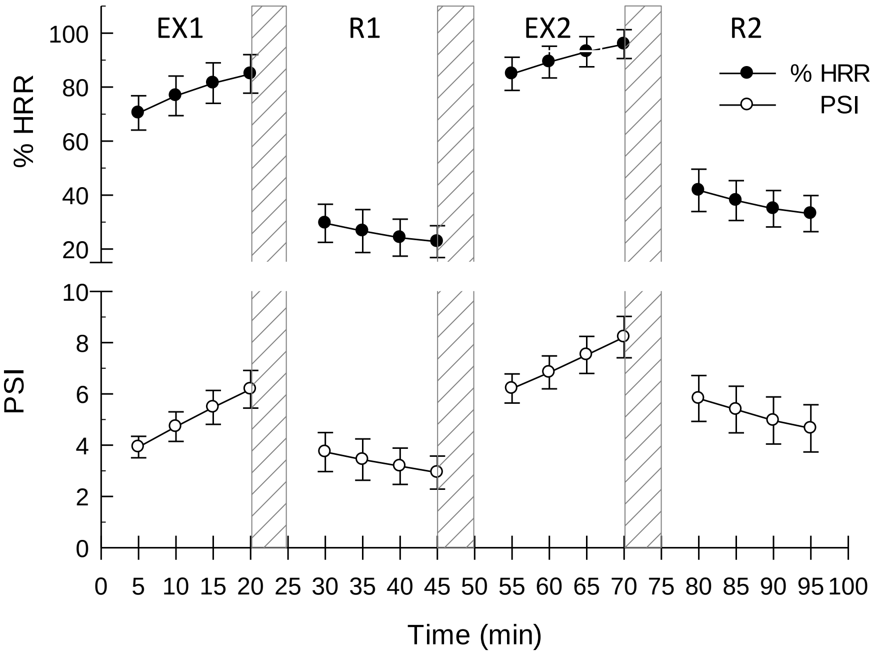

Figure 2.8. Mean (± SD) pooled percentage of heart rate reserve (% HRR) and the physiological strain index (PSI). Shaded bars represent the transitions between exercise and recovery periods which were approximately five minutes in duration.

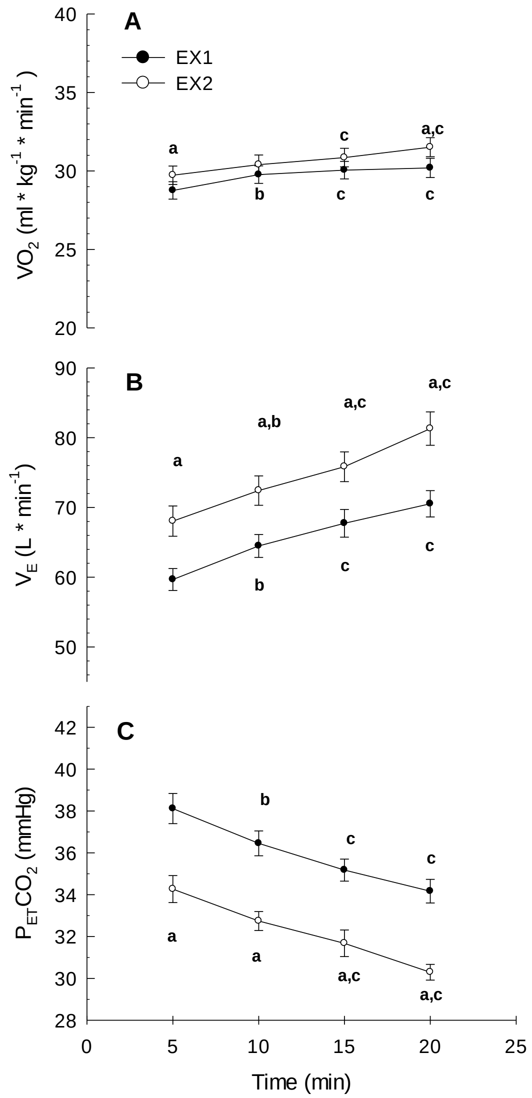

Figure 2.9. The mean (± SE) pooled relative oxygen consumption (VO_2), minute ventilation rate (V_E BTPS) and partial pressure of end tidal carbon dioxide ($P_{ET}CO_2$) responses at five minute intervals during the first (EX1) and second (EX2) 20 min exercise periods. Panel A depicts the relative oxygen consumption (VO_2) ($n = 12$). Panel B depicts the minute ventilation rate (V_E BTPS) ($n = 12$). Panel C depicts the partial pressure of end tidal carbon dioxide ($P_{ET}CO_2$) ($n = 9$). '**a**' denotes significantly different than the value at the same time point during EX1 ($p < 0.001$). '**b**' denotes significantly different than the 5 min value within the same exercise period ($p < 0.05$). '**c**' also denotes significantly different than the 5 min value within the same exercise period but at a significance of $p < 0.001$.

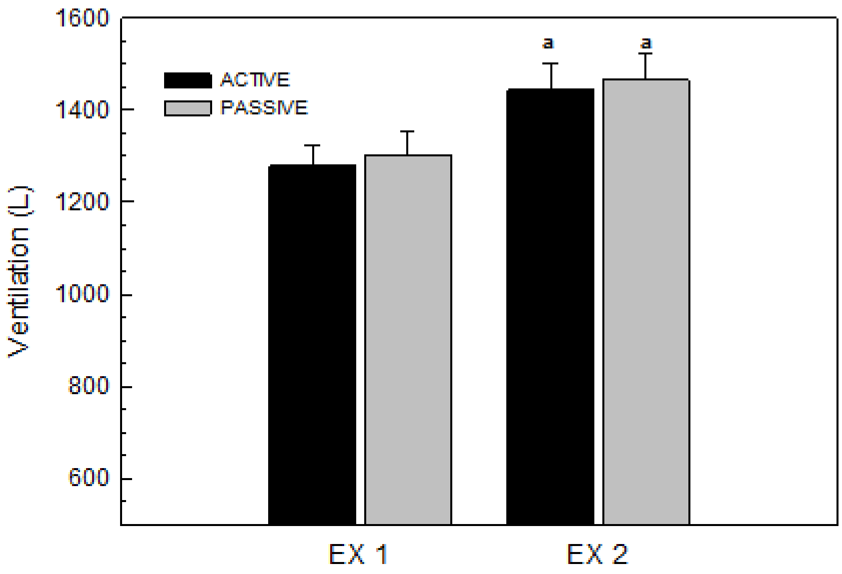

Figure 2.10. Total ventilation BTPS (mean ± SE) during each 20 minute exercise period (‘**a**’ denotes significantly different than EX1, $p < 0.001$).

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Chapter 3

General Discussion

3.1 Future Directions

Core temperature can be reduced by two degrees (from 39.5°C-37.5°C) in 2-3 minutes with full body immersion. Taylor et al. (2008) demonstrated that this was possible with either cold (14°C) or tepid (23°C) water and that it was 8-10 times faster than cooling passively in temperate ambient air (20°C - 22°C). Whole body immersion would likely be preferred to regional cooling at all times, but this is not possible when wearing protective clothing. Determining the effects of regional cooling countermeasures such as AC and PC is warranted when environments do not allow access to the whole body and when UHS is unavoidable.

The present study has demonstrated that head exposure, while the remainder of the body was encapsulated, lowered core temperature by 0.3°C -0.5°C in 20 minutes. The amount of cooling depended on condition (AC or PC) and heat storage. Despite these decreases in core temperature, heat storage was cumulative because of factors such as an overshoot in temperature after exercise. Combining AC or PC with another regional cooling countermeasure or cooling technique may have added to heat loss and prevented these cumulative effects. If multiple countermeasures can provide additive effects then various combinations should be investigated.

There was a significant interaction between condition and time during the second recovery period which led to an examination of the individual results (Figure 2.1 and 2.3). The high individual variability in responses suggests that adding more subjects would not necessarily have improved the power of the analysis. Individual subjects responded very favourably to both AC and PC and others did not respond to either condition. The interaction effect was the result of some, but not all, subjects responding favourably to AC. Only absolute core temperature was significantly correlated with AC during R2.This is partly consistent with previous research (Rasch et al. 1991). To further test this hypothesis a more standardized heating protocol may be useful. If all individuals were heated to the same core temperature, before cooling, the variability of cranial cooling under active and passive conditions could be measured across individuals in relation to absolute temperature.

Targeting the cranium neck and face has received much attention because of the disproportionate effects that result from cooling this anatomical region. Koscheyev et al. (2002) attempted to develop individual thermal profiles based on body regions which demonstrated the greatest heat flux. Koscheyev et al. (2002) speculated that the head was not sensitive enough for determining whole body thermal profiles because it was too well perfused across a range of environmental temperatures. Because of the relatively stable heat flux of the head, Koscheyev et al. (2002) recommended targeting other body regions when developing individual thermal profiles. The results of Koscheyev et al. (2002) suggest that the head's ability as a heat sink is almost always fully exploited which was somewhat at odds with the present results. The present study demonstrated that active heat removal from the head could result in greater reductions in core temperature during R2. The individual results also suggest that heat removal from the head may be more effective in some individuals than others. Identifying individual factors which affect head cooling and directly comparing active to passive heat flux could help to answer these questions.

Based on the cooling capacity measured during the present study (approximately 35 W) the classification of cooling hoods made by Epstein et al. (1986) who used a similar hood (~34 W) appears to be most relevant (see Table 3.1). Epstein et al. (1986) ranked cooling hoods as Class C based on physiological strain ($\Delta HR/100 + \Delta T_{rectal}$ + Sweat Rate). This ranking was inferior to liquid cooled vest and ice vest but superior to air cooling hoods and vests. This classification does have limitations. It should be noted that the results provided by Epstein et al. (1986) demonstrated a significant effect of hood cooling on both core temperature and physiological strain. Cooling vests can access a greater surface area and intuitively should be more effective however, exposing a greater surface area to cooling is not always possible and is not always superior to regional cooling (Barr et al. 2011). Barr et al. (2011) found that the addition of an ice vest to forearm submersion (FS) did not lower core temperature any more than forearm submersion alone.

Cranial cooling is a regional cooling countermeasure and can be considered relative to other regional cooling approaches such as FS. Based on the current literature FS is the most effective and reliable choice for regional cooling of the extremities (Selkirk et al. 2004; Barr et al. 2011; DeGroot et al. 2013). The effects of forearm submersion on core temperature, while encapsulated, have also demonstrated considerable variability (DeGroot et al. 2013). When regional cooling has been used the magnitude of physiological effects appears to depend on the level of encapsulation, the ambient environment, the subject's state (rested or recovering) and the duration of cooling (DeGroot et al. 2013).

The present protocol did not make a direct comparison to any other countermeasure such as forearm submersion however, AC and PC both influenced heat storage and decreased core temperature. The interaction effect observed during R2 suggests that, similar to FS, the effects of cranial cooling increase or decrease depending on the protocol. Whether widespread use of cranial cooling is worthwhile requires further research to determine with which protocol it can be used most effectively.

Table 3.1. A summary of different liquid cooling garments which targeted the head and their effects at rest, during exercise or during recovery.

Study	n	Hood configuration			Duration	Core temperature effects	Ambient conditions
Author		Tubing type and surface area	Flow rate ($L \cdot min^{-1}$)	Water temperature (°C)	Time and condition	Head cooling vs. control or Initial (I) to Final (F)	Including head heat extraction results if available
Shvartz, (1970)	6	1100 cm, 3% BSA	0.8	5°C	120 min of Walking ($5\ k \cdot hr^{-1}$)	38.5 vs. 37.9 (Δ 0.6°C) (Rectal)	50°C, 20% R.H. ~183 W
Nunneley et al, (1971)	3	1350 cm, of Tygon® tubes	0.360	22°C during rest	120 min of walking (50% VO_{2max})	Ambient 20°C 38.3 vs. 38.4 (Δ ~0.1 °C) (Rectal)	Ambient 20°C 60 ± 18 W
				5°C during EX		Ambient 30°C 38.6 vs. 38.5 (Δ ~0.1°C) (Rectal)	Ambient 30°C 67 ± 11 W
						Ambient 40°C 39.0 vs. 39.4 (Δ 0.4°C) (Rectal)	Ambient 40°C 95 ± 16 W
							At rest 28 ± 4 W
Nunneley et al, (1982)	6		0.7	8 °C	45 min seated between heating and cooling.	I 38.5 ± 0.3 to F 38.5 ± 0.3 (Δ 0.0°C) (Rectal)	

						I 38.3 ± 0.3 to F 38.6 ± 0.2 (Δ 0.3°C) (Esophageal)	
Nunneley and Maldonado (1983)	8	0.054 m^2	0.80	15.5°C	90 min seated	37.5 ± 0.2 vs. 37.8 ± 0.2 (Δ 0.3°C) (Rectal)	Dry bulb 35°C; Wet bulb 26°C, Black globe 43°C 45% R.H.
Epstein et al, (1986)	8	950 cm, $0.05m^2$	0.06	12°C	240 min seated	37.41 ± 0.08°C vs. 37.80 ± 0.04°C (Δ 0.39°C) (Rectal)	50°C, 20% R.H. ~34 W
Katsuura et al, (1996)	7	Ten Tygon® tubes, 2mm radius	1.8	10°C	40 min Seated after 50 min of exposure	Frontal cooling I 37.1 ± 0.12°C to F 37.4 ± 0.14°C (Δ 0.3°C) (Rectal) Occipital cooling I 37.1 ± 0.05°C to F 37.3 ± 0.04°C (Δ 0.2°C) Temporal cooling I 37.4 ± 0.12°C to F 37.5 ± 0.10°C (Δ 0.1°C)	40°C, 50% R.H. Frontal 47 ± 2.3 W Occipital 29 ± 5.4 W Temporal 75 ± 4.6 W

						No cooling I 37.2 ± 0.15°C to F 37.5 ± 0.16°C (Δ 0.3°C)	
Palmer et al, (2001)	14	PVC 630 cm	1.1	1°C	1. 60 min seated 2. 30 min running at 60% VO_{2max} Then 15 min maximal distance A. No cooling during 2. B. No cooling during 1. C. Cooling during 1 & 2.	All cooling conditions Δ -0.15 to - 0.20°C vs. control after precooling (Rectal + esophageal/2) All cooling conditions Δ -0.20 to -0.25°C vs. control after exercise (Rectal + esophageal/2)	33°C, 55% R.H. During 1. 1 A. ~143 W During 2. 2 B. ~178 W 2 C. ~157 W
Kim et al, (2011a)	6	18°C	TCG 0.20 SCG 0.65		Three exercise stages at 75% VO_{2peak} separated by 10min of recovery.	TCG had no effect on T_{core} but lowered HR during recovery. SCG significantly lowered T_{core} and HR.	35°C, 50% R.H.

3.2 References

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Appendix A

Review of the Literature

This review will help outline the debates, the behaviour, and the mechanisms of hyperthermia, fatigue and exhaustion. It will then describe the role of cooling countermeasures and the potential of active cranial cooling.

A.1 Thermal physiology

Chemical to mechanical energy transfer is inefficient. The majority of potential energy used to produce high energy phosphates is released as heat (Cheung. 2010a). Heat transfer within or between the body and the environment will occur along gradients through a combination of radiation, conduction, convection and evaporation. Heat exchange between the body and the environment is described by the heat balance equation (Holmer. 2006, Cheung et al. 2000). Because heat exchange also depends on the surface area available, heat balance is typically expressed in watts per metre squared ($W \cdot m^2$).
A typical expression of the heat balance equations is:

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

Heat gain is represented by S. Metabolic energy production is represented by M. mechanical work (W) is typically subtracted and Radiation (R), Conduction (C), convection (K), and evaporation (E) round out the calculation. Evaporation or sensible heat loss is the primary mechanism of heat release during exercise (Cheung et al. 2000).

The evaporation of 1L of sweat can dissipate about 2344 kJ of energy. During exercise in Fire Protective Ensemble (FPE) there is a diminished capacity for evaporative cooling. The microclimate beneath the clothing diminishes the water vapour pressure gradient and draws the point of evaporation away from the skin surface (Cheung et al. 2000). Eliminating this pathway will lead to Uncompensable Heat Stress (UHS). A Heat Stress Index (HSI) where $E_{required}$ (the total evaporative heat loss required for thermal balance) exceeds E_{max} (the total evaporative heat loss potential of the environment), or any value greater than one (>1.0) defines the uncompensable condition (Cheung et al. 2000).

A.2 Recent models of Fatigue and Exhaustion during Hyperthermic Exercise

Aerobic capacity is impaired by hyperthermia (Galloway and Maughan. 1997, Gonzalez-Alonso and Calbet. 2003). Heat balance is difficult to achieve when metabolic and environmental heat gain combine. A summation of thermal regulation mechanisms will eventually conflict with performance (Cheung and Sleivert. 2004, Cheuvront et al. 2010). Impairment can be characterized as decreased maximal performance or premature fatigue and exhaustion. Behavioural adjustments (pacing strategies) can help to prolong endurance at the expense of work rate (Cheung. 2007, Schlader et al. 2011b).

Cheung and Sleivert (2004) suggest that the interaction of multiple triggers cause fatigue and exhaustion. These triggers are high brain temperatures, hyperventilation, hypoglycemia, and decreased gut blood flow. While these four factors may or may not always interact, when present each can have a direct effect on exercise performance. Confounding the research of fatigue causing mechanisms is that hyperthermia is typically brought about with exercise resulting in elevated cardiovascular strain.

Cheuvront et al. (2010) have reviewed heat related performance impairment and focus on cardiovascular strain as the primary source of fatigue and exhaustion. They argue that cardiac output is most often the limiting factor. The increased demand for blood flow to the brain and skin will decrease cardiac output to working muscle. Physical exhaustion can occur at a continuum of core temperatures when cardiac output does not meet the demands of work. Increases in skin blood flow are highly correlated to increase in skin temperature. The disappearance of the core to skin thermal gradient can become a predictor of fatigue and exhaustion. Further declines can also result from the direct effect of heat on the contractility and rhythm of the heart (Cheuvront et al. 2010).

Johnson. (2010) has reviewed that increases in skin blood flow reach an upper limit when core temperatures reach 38°C. This limit is well below the full potential of skin blood flow and when adrenergic skin function is abolished this limitation persists ((Johnson 1974). Therefore there is an upper limit to how much blood will be diverted to the skin. This phenomenon is explained as a safeguard to limit cardiac strain in situations with critical thermal and circulatory demands (Johnson. 2010).

The passive heating protocol used by (Morrison et al. 2004) has demonstrated that passively increasing core temperature to 39.5°C can impair voluntary activation (VA) and maximal voluntary contractions (MVC) despite only moderate cardiovascular strain (65 % heart rate reserve). Upon cooling, a rapid decrease in skin temperature had no effect on VA or MVC however, as core temperature decreased both VA and MVC were restored to baseline intensities (Morrison et al. 2004). Therefore, without the confounding cardiovascular strain of exercise and high demands for peripheral skin blood flow, heat storage alone impaired muscular contractions. Core cooling, not skin cooling restored them. During hyperthermia competition for cardiac output can be a factor of performance impairment; however, there is also strong evidence to support multiple triggers when cardiovascular strain and skin blood are not the primary stressors during hyperthermia. The combination of many detrimental factors is ultimately responsible for fatigue and exhaustion (Cheung and Sleivert. 2004).

A.3 Selective Brain Cooling and its Occurrence in Humans

High brain temperature is one potential predictor of exhaustion during hyperthermia (Cheung and Sleivert. 2004). Some animals have adaptations to selectively cool the brain which helps prevent heat storage. The human ability to selectively cool the brain (SBC) is controversial (the interested reader can follow the “POINT: COUNTERPOINT”, “Rebuttals”, “Last words”, and “Comments” between White et al. (2011) and Nybo and Secher (2011). To achieve SBC the temperature of the brain must be lower than the temperature of the brain’s arterial blood supply. White et al. (2011) contend that there are three adaptations to facilitate SBC in humans: direct surface heat loss from the cranium, counter-current heat exchange between arteries and veins, and thermal hyperpnea. Nybo and Secher (2011) discount the ability of both the cranium and airways to dissipate substantial enough amounts of heat, and deemphasize the contribution of counter-current cooling of venous-arterial blood.

In humans, the carotid arteries and vertebral arteries make up the systemic link from the heart to the head (Querido and Sheel. 2007). Arterial blood passing through these arteries converges at the Circle of Willis which supplies the main arteries of the brain, including the middle cerebral artery (MCA) (Querido and Sheel. 2007). The average blood flow to the brain is 750 $ml \cdot min^{-1}$, which is 15 % of the total cardiac output (Querido and Sheel. 2007). Counter-current heat exchange on the anterior neck’s superficial bundled structure as well as between the cavernous sinus and the internal carotid arteries, have been suggested as promising sites for active cooling (White et al. 2011, Wang and Zhu. 2007). Nybo and Secher (2011) contend that the transit time from the aortic arch to the brain is too rapid to allow any substantial counter current cooling. Nybo et al. (2002) demonstrated that throughout exercise the temperature of blood entering and exiting the brain remained higher than esophageal body temperature. Blood velocity actually decreased during hyperthermic exercise. These results indicate an inadequate heat release from the brain rather than a reliance on counter-current heat exchange (Nybo and Nielsen. 2001).

Nybo et al. (2002) also observed that hyperventilation was a possible trigger for the slowing of brain blood flow. Hyperventilation would lower $PaCO_2$, cause vasoconstriction and reduce blood flow through the brain. During exercise this reduced convection of blood and increased brain metabolism (glucose utilization) would result in greater heat storage. All of these events are consistent with the model of fatigue and exhaustion as outlined by Cheung and Sleivert. 2004).

The purpose of decreased MCA velocity may be to shield the brain from incoming overheated blood (Sukstanskii and Yablonskiy. 2007). During recovery from hyperthermic exercise, decreased MCA velocity is sustained for up to an hour (Nybo et al. 2002). This after effect may retard the effect of convective cooling during recovery.

Two limitations when discussing SBC are the difficulty in measuring brain temperatures and the non-uniform distribution of temperatures within the brain. The temperature and flow of blood in the MCA are not easy to measure (Querido and Sheel. 2007, Nybo and Nielsen. 2001) and neither are the temperatures of the carotid artery or jugular vein (Nybo et al. 2002). The validity of tympanic temperature as a surrogate of brain temperature is questionable, supported by some (White et al. 2011) and is discounted by others (Nybo and Secher. 2011, Simon. 2007).

Under normal circumstances SBC seems unlikely; however, surface heat losses from the cranium, counter-current heat exchange between arteries and veins, and thermal hyperpnea can be enhanced with the use of active cooling devices (ACDs). When applied, ACDs have the potential to lower brain temperatures (Sukstanskii and Yablonskiy. 2007, Harris et al. 2008, Boller et al. 2010). Harris et al. (2008) demonstrated that 30 minutes of forced convective hood cooling could lower mean brain temperature by 0.45°C. Cooling took place at rest while circulating air (14.5°C) through a tube lined hood at a flow rate of 42.5 $L \cdot s^{-1}$. Changes in brain temperature were measured by magnetic resonance spectroscopy.

Computer models of active brain cooling by external devices generally predict that the thickness and conductivity of the cranium prevents deep cooling of the brain (Nelson and Nunneley. 1998). Models which support brain cooling predict that only the outer most layers of the brain can be cooled. This is most likely where a high coefficient of heat transfer from the brain to the cooling device exists such as the thin cranium of infants (Sukstanskii and Yablonskiy. 2007). Nelson and Nunneley (1998) attribute the measurable benefits of cranial cooling to perceptual rather than thermal physiological effects.

Although direct conduction through the scalp is not supported by computer modeling, White et al. (2011) highlight the possibility of a convective pathway through the scalp via valveless emissary veins which drain into the cavernous sinus; a location were counter current heat exchange might take place.

A.4 The Rational for Cranial Cooling

Convective hood cooling can lower body temperature. For example, Reynolds et al. (2011) found 60 minutes of hood cooling with 10°C significantly reduced rectal temperature (Δ0.31°C) in rested multiple sclerosis patients. If the body can be cooled, and core temperature reduced, then the brain may still benefit from incoming cooled blood. Directly measuring whether a cranial cooling device has the potential to lower brain temperatures is beyond the scope of this study, however, the ability of active cooling devices to lower core temperature demonstrates that the potential of cranial cooling is not limited to brain cooling.

Rasch et al. (1991) quantified evaporative, convective, conductive and radiant heat loss from the human head and airways during exercise. They determined that the head can be a heat sink and that skin on the head was able to liberate between 50 W and 150 W of heat at different exercise intensities. At rest, these amounts were between 12 W and 29 W depending on the ambient temperature. Higher exercise intensities and ambient temperatures produced greater quantifiable heat loss. Their measurement method, a plastic hood, resulted in convective circulation at a speed of about 0.8 $m \cdot s^{-1}$ and the authors commented on the value of convection cooling of the head so long as the evaporative cooling potential is preserved.

Katsuura et al. (1996) found that the forehead was more sensitive to cooling in a hot environment than was cooling the occipital or temporal regions. They independently cooled each section using a tube lined shroud while seated in a hot humid environment (40°C 50 % R.H.). Cooling these surface areas had no significant effect on rectal temperature which increased 0.1°C to 0.2°C during 30 minutes of exposure. Thermal comfort was significantly affected by forehead and occipital cooling and thermal sensation was significantly affected by temporal cooling.

Several studies by Pretorius et al. have described the cooling potential of whole head compared to whole body immersion in cold water (Pretorius et al. 2006, Pretorius et al. 2008, Pretorius et al. 2010). They found that the head can disproportionately lower esophageal temperatures given its surface area. Their method used selective head immersion adjusted to different depths around a prone or supine subject. Pretorius et al. (2010) demonstrated, that during 30 minutes of dorsal, facial, or whole head immersion in cold water (17°C), cooling rates at the esophagus increased respectively from $0.29 \pm 0.2°C \cdot hr^{-1}$ to $0.47 \pm 0.1°C \cdot hr^{-1}$ to $0.69 \pm 0.2°C \cdot hr^{-1}$. From these results Pretorius et al. (2010) concluded that the dorsum and face have different but cumulative cooling potentials where whole head cooling resulted in the most heat loss.

A.5 The Effects of Active Head Cooling, at Rest and During Exercise

A.5.1 Hood cooling

Early attempts at hood cooling by Shvartz (1970) found that a tube lined hood circulating water 5 ± 0.5°C and a flow rate of 0.8 $L \cdot min^{-1}$, could maintain a lower rectal temperature (37.9 vs. 38.5 $p < 0.001$), and heart rate (126.8 vs.

147.6 $p < 0.001$) compared to a control condition during 2 hours of treadmill walking (5 $km \cdot h^{-1}$) in the heat (50°C, 20 % R.H.).

Nunneley et al. (1971) found that a water perfused hood was able to remove 30 % of resting and 19 % of exercising metabolic heat production while walking for two hours at 50 % VO_{2max}. The flow rate through their hood was 0.360 $L \cdot min^{-1}$ and water the temperature varied between rest (22°C) and exercise (5°C). Cooling was improved when colder water temperatures were gradually applied after the start of exercise. The authors found that rapid cooling, applied before the increase in core and skin temperature, resulted in peripheral vasoconstriction. Early onset of vasoconstriction may have impaired the overall cooling effect of the hood during exercise by diminishing vasodilation and skin perfusion.

Further investigation found that head cooling was able to maintain reaction time and accuracy while the body was passively heated to 39°C. Although head cooling did not alter rectal temperature it did alter the increased rate of esophageal temperature. In certain individuals head cooling also reduced peak esophageal temperature (Nunneley et al. 1982).

Nunneley and Maldonado (1983) were able to follow up this work while investigating the effects of head and/or torso cooling during simulated cockpit heat stress. With water temperatures of 15.5°C and flow rates of their water perfused hood influenced heart rate, rectal temperature, as well as whole body and forehead sweat rates. Measurements took place after 10 minutes of light exercise while seated and resting for 90 minutes in full flight gear. Ambient conditions were set to mimic those of a cockpit (dry bulb temperature of 35°C; a wet bulb temperature of 26°C, a black globe temperature of 43°C and 45 % R.H). Although the effects of head cooling were not significant they were persistent across measures and their lack of significance may have been due to a small sample size (n = 8). It was found that head cooling was 2-3 times more efficient per amount of surface area cooled than torso cooling (3 - 4 % BSA for the head compared to 14 % BSA for the torso). Some of the advantages of hood cooling proposed by the authors were that: the head provides an interface for cooling with water temperatures as low as 5°C; that wearing a hood did not remove the potential for evaporative cooling across the rest of the body; and that hood use avoided limb encumbrance.

Epstein et al. (1986) compared and rated a variety of cooling technologies including water and air perfused suits, zone air convective cooling, ice-bag vests, and fanning. They cooled each subject during 4 hours of seated exposure to a hot dry environment (50°C, 20 % RH). The cooling hood circulated 12°C water at a flow rate of 0.06 $L \cdot min^{-1}$ which amounted to a cooling capacity of approximately 34 W. Compared to a control condition, hood cooling improved total heat dissipation (121.6 ± 2.0 $W \cdot m^{-2}$ vs. 111.8 ± 3.3 $W \cdot m^{-2}$), maintained a lower rectal temperatures (37.41 ± 0.08°C vs. 37.80 ± 0.04°C), and decreased heart rate (HR) (78 ± 3 $b \cdot min^{-1}$ vs. 102 ± 3 vs. $b \cdot min^{-1}$) as well as Sweat Rate (SR) (218 ± 27 $g \cdot m^{-2} \cdot hour^{-1}$ vs. 328 ± 32 $g \cdot m^{-2} \cdot hour^{-1}$) while preserving 78 % of evaporative heat loss across the rest of the body. Epstein et al. (1986) determined that hood cooling had less effect on the physiological strain index ($\Delta HR / 100 + \Delta T_{rectal} + SR$) compared to vest cooling. Hood cooling resulted in significant physiological effects despite this comparison vest cooling. The authors suggested that future research needed to investigate active cooling before and after exercise.

Palmer et al. (2001) used water a perfused hood and compared a control condition to cooling either before, during, or before and during a rest followed by a run (approximately 60 % VO_{2max} for 30 minutes) followed by a 15 minute, maximal distance sprint. Head cooling, in a hot environment (33°C, 55 % RH), improved the perceptual responses at the end of all trials. Core temperature (rectal + esophageal/2) was lower in all cooling trials by 0.20 - 0.25°C and HR was unchanged (Palmer et al. 2001). Sprint performance only improved when cooling was applied before and during exercise. The hood circulated water at a rate of

1.1 L·min^{-1} at a temperature of 1°C. The heat loss potential of the hood was calculated to be between 143 W at rest and up to 178 W during exercise.

Warpeha (2010) found that the addition of a cooling hood to two different full body liquid cooling garments had no effect on core temperature or heart rate. Two ambient conditions (24°C and 34°C) were used and a 6 x 20min protocol was used. Three 20 min periods of treadmill walking at 250 W, 300 W and 400 W were followed by a 20 minute recovery period, then by two 20 min periods of hard exercise (700 W and 500 W) and a second 20 min recovery period. Cool water (15°C) was circulated through the garments during the entire 154 min protocol. Warpeha (2010) still emphasized the attributes of targeting the head particularly accessibility and the benefit of heat loss from a region with very little cold mediated vasoconstriction. Two identified limitations of their study, in regards to head cooling, were the insulative effects of hair and the 15°C temperature selected. Warpeha (2010) also compared the different LCGs based on flow rates and found that high flow rates were not necessarily superior to low flow rates. Although skin temperature varied considerably with greater flow, core temperature did not.

The design and fit of cooling hoods is of critical importance to their ability to remove heat. (Kim and LaBat. 2010, Flouris and Cheung. 2006) Good designs cover a large surface area, cover a vascular dense area, are in direct contact with the skin and promote minimal heat exchange with the outside environment (Nunneley et al. 1971, Kim and LaBat. 2010, Flouris and Cheung. 2006). The selection of fabrics and tubing materials which maximize flexibility and allow high rates of conduction from the body are important (Nunneley et al. 1971, Kim and LaBat. 2010, Flouris and Cheung. 2006). A detailed outline of the utility and limitations of water perfused garments can be found in the review by Flouris and Cheung (2006) and the multi-disciplinary approach necessary to design and test a cooling hood can be found in the analysis of Kim and LaBat (2010).

A.5.2 The Perceptual Responses to Skin Cooling

Flouris (2011) emphasises that behavioural responses to thermal comfort serve the greatest role in human thermal regulation whereas autonomic and neuroendocrine responses to thermal sensation are less able to maintain homeostasis in stressful environments. Therefore the perceptual effects of head and face cooling have the potential to lead and mislead thermoregulatory behaviour and heat loss or heat gain.

The cranium, neck and face are particularly sensitive to increases in skin temperature which can heighten both the perception (Arens et al. 2006) and the physiological responses to hot environments (Rasch et al. 1991, Pretorius et al. 2006, Pretorius et al. 2008, Cotter and Taylor. 2005). Arens et al. (2006) found that in warm environments the head is more sensitive to perceptions of heat than other body regions. Overall, these researchers made the simple but important observation that comfort follows the warmest local sensation (the head) in warm environments.

Cotter and Taylor (2005) applied small patches to various skin sites while clamping the overall skin and core temperature with a water perfused suit. Changes to temperatures of the face compared to other body regions had the greatest effects on thermosensitivity when both heating and cooling were applied to a forehead patch. Local sweating rates (M_{sw}) and local skin temperatures (T_{skl}) were measured and thermosensitivities were quantified based on a combination of M_{sw} and T_{skl}. The face displayed 2-5 times the sensitivity to cold stimuli compared to other body regions. During warming, the facial sweating response increased to 60 % of baseline, which was 10 to 20 % more than the response of any other region. During cooling facial sweating decreased more rapidly than other regions. These findings suggest two potential outcomes. Firstly, while facial cooling can relieve the perception of heat stress, this may prematurely decrease sweat rate and impair evaporative heat loss. Secondly, if heat removal could be sustained, sweat rates could decrease and hydration could be better maintained. Heightened cutaneous and deep tissue thermosensitivities might be the peripheral mechanisms behind heightened thermal perceptions (Arens et al. 2006, Cotter and Taylor. 2005).

Partial removal of protective clothing during exercise may have improve comfort. Montain et al. (1994) demonstrated that when the head, hands and face were exposed physiological strain was reduced. Each subject was required to complete four trials while partially clothed. Exercise intensity (moderate or high) and the ambient conditions (hot and dry or hot and wet but with equal wet bulb globe temperature 30°C) were manipulated. Fully encapsulated subjects reached exhaustion sooner compared to when partially exposed (46 ± 11 min compared to 100 ± 27 min during hot dry conditions). Core temperature was lower at exhaustion when fully encapsulated because there was less time for heat storage to occur. One explanation for exhaustion was cardiac drift. During the fully encapsulated condition mean skin temperature was 0.4°C higher and the increased skin blood flow may have resulted in a reduction in the cardiac reserve. Another potential explanation was that subject comfort was improved when the head hands and face were exposed. The positive results of partial clothing on tolerance to exercise leads to the question; what effect does similar exposure have on recovery and subsequent exercise? Particularly if head exposure is combined with active heat removal which is known to have physiological effects.

A.5.3 Facial Cooling

Armada-da-Silva et al. (2004) demonstrated that facial cooling during exercise was able lower HR and decrease Ratings of Perceived Exertion (RPE) after preheating the subject to a core temperature of 38.5°C. Facial cooling did not lower core body temperature but it did lower concentrations of the hormone prolactin (Armada-da-Silva et al. 2004). Prolactin is released from the pituitary in response to increases in brain temperature. The release of prolactin has been associated with a decreased drive to exercise (Mundel et al. 2007, Ansley et al. 2008). The pituitary gland is located just below the hypothalamus in the *sella turcia* which is close to both the nasal airways and the trigeminal nerve; this location may be susceptible to SBC or to sensations of cooling stemming from the face and ears via the trigeminal nerve. Changes to the release of prolactin and the potential of local cooling or cooling sensations to reach the temperature centers of the brain have led to other studies which investigate the perceptual effects of facial cooling.

Mundel et al. (2007) and Ansley et al. (2008) both investigated the effects of exercise in the heat with facial cooling. Facial cooling attenuated the increase in plasma prolactin concentrations and lowered ratings of perceived exertion. Similar to the results of Armada-da-Silva et al. (2004), core temperature was not significantly reduced by facial cooling (Mundel et al. 2007, Ansley et al. 2008). Additionally, Ansley et al. (2008) found that facial cooling increased exercise time to fatigue at 75 % VO_{2max} in 8 of 9 participants.

Cheung (2010b) presented the dilemma of separating the effects of thermal perception and thermal stress. This review recommends the development of experimental methods for the brain to perceive a different thermal status than what the body is truly experiencing (Cheung. 2010b). The effect of menthol, a topical agent which simulates cold sensations but does not cool the skin, may address this need. Jointly, menthol application may: increase ventilation and exercise time (Mundel and Jones. 2010), decrease skin blood flow and raise core temperature (Olive et al. 2010, Kounalakis et al. 2010, Lee et al. 2012) and increase the perception of fatigue without changing core temperature (Gillis et al. 2010). Gillis et al. (2010) point out the limitations of menthol including different responses to different concentrations and inconsistent responses depending on the method of application and the mixture used.

Relevant to head cooling, Schlader et al. (2011a) found that an 8 % menthol gel applied to the face significantly improved exercise time and rate of power output drop in hot, humid conditions. The menthol rub also significantly decreased facial and whole body thermal discomfort. Both of these results were almost as significant as when the face was cooled. The similarities between the benefits of actual face cooling and perceived face cooling help reinforce the idea that the head region affects thermal perceptions and behaviour in the heat and that the effects may improve comfort and tolerance.

In a recent study to investigate the effects of menthol and exercise in FPE, Lee et al. (2012) demonstrated that a 0.8 % menthol rub caused increased heat storage when applied to the whole or upper body. The same menthol solution had no effect when applied to only the face and neck. The authors speculated that evaporative cooling was impaired by the menthol rub. The lack of effect in the face and neck condition was attributed to the high conductive and convective potential of the head which was not altered by menthol. Physiological strain index (PSI), the combined measure of core temperature and heart rate, was lowest when menthol was applied to the face and neck but no perceptual responses were changed. Despite the appeal of improved thermal comfort, the use of menthol as a countermeasure was not deemed worthwhile when physiological effects were impaired or masked. The authors concluded that in hazardous environments where protective clothing is used, the safety of those at work would be jeopardized by the effects of menthol.

Kim et al. (2011b) found that a top cooling garment (covering the head and forearms) decreased heat perception while not having any effect on thermal comfort. Subjective ratings of fatigue were not diminished by the cooling intervention until the end of a third exercise period. Their cooling intervention was applied throughout the protocol which required the completion of three fifteen minute periods of intermittent exercise (75 % VO_{2peak}) interspersed by ten minute periods of recovery. They also evaluated physiological strain using the scale developed by Moran et al. (1998) and found that the top cooling garment (TCG) had no physiological effect. Using a short cooling garment (covering the head, forearms, torso and thighs) resulted in similar perceptual effects but also significantly reduced the physiological strain. The SCG but not the TCG was recommended as a countermeasure for uncompensable heat stress.

A.6 Individual Responses to Cooling and UHS

Nunneley et al. (1971) reported the individual rectal temperatures of three subjects to head cooling after 2 hours of moderate exercise. Overall head cooling had almost no effect in a 20°C environment. In a 30°C environment the responses were more varied. Subject A responded, core temperature remained 0.7°C lower with head cooling. Subject B maintained a low rectal temperature regardless of cooling. Subject C had an inverted response and actually stored more heat when head cooling was used (39.0°C with head cooling and 38.3°C without). In a 40°C environment all subjects stored less heat when head cooling was used. Subject B remained 0.9°C cooler with head cooling and subject A and C both remained about 0.3°C cooler. Head cooling responses in this small sample were highly variable. All three subjects only responded when compared to the high rectal temperatures (39.4°C) achieved when cooling was not applied and exercise took place in a 40°C environment. When all three subjects did respond one of the three had a change in temperature three times more beneficial than the others.

Tikuisis et al. (2002) found that there was a wide variety in individual responses to temperature loss in a cold environment following a long period of exercise. Body composition and metabolic rate were determined to be the main contributors to differences amongst individuals. Leaner and less metabolically active subjects tended to be those who cooled most rapidly.

Koscheyev et al. (2002) developed a compartmentalized liquid cooling garment and found that individual variability during cooling was greatest in regions with lower density such as muscle and adipose compared to tissues of higher density such as connective tissue and bone. Body temperature was thermal stabilised with 33°C water while different regions were exposed to 20 min at 8-10°C, 15°C, 28°C, 38°C, or 45°C water. The least dense regions (the torso, thighs and shoulders) tended to have the greatest surface areas and provided the greatest total heat flux. The high density regions (the hands and head) tended to be highly perfused and heat flux was most efficient (energy per unit area) in these regions. Koscheyev et al. (2002) recommended that the areas of greatest variability (the torso, thighs and shoulders) be targeted for thermal profiling because they offered they were more sensitive across a range of temperatures.

Euhydration but not acclimation appears to benefit tolerance time and offset heat storage during exercise (Cheung and McLellan 1998). Ten sessions of acclimation over 2 weeks resulted in increased sweat rates and a decrease in HR. Tolerance time did not improve and there was no significant effect on the change in core temperature. Heat acclimation had a greater effect on trained compared to untrained subjects however the decreased physiological strain was not able to improve tolerance (Cheung and McLellan 1998). With hypohydration (-3 % body mass) tolerance time was significantly reduced, with and without acclimation and in both trained and untrained groups. Euhydration and rehydration strategies were emphasized as the key strategies to improve tolerance.

Subjects classified as trained with low adiposity (T_{Low}) demonstrated superior tolerance time, heat storage and peak rectal temperatures while exercising in an UHS environment (Selkirk and McLellan 2001). A group of trained high adiposity (T_{High}) subjects also demonstrated benefits over the untrained high (UT_{High}) and low (UT_{Low}) adiposity matched groups. The reason for termination for all T_{Low} subjects was attainment of the cut-off rectal temperature (39.5°C) whereas this was only the case for one of six T_{High}, none of the UT_{Low} and only 2 of the UT_{High}. Increased tolerance times characteristic of the trained groups was attributed to the ability to tolerate higher rectal temperatures at exhaustion. Having less adipose tissue, which due to its density can reduce the heat storage capacity of the body, may have also contributed to the achievement of higher rectal temperatures independent of training status. Interestingly a third factor which affected heat storage was economy. The UT_{High} group were able to walk with a reduced oxygen cost relative to their mass which helped them to offset heat storage.

Many factors are known to influence heat storage and heat loss. A comprehensive method for evaluating the susceptibility of individuals to regional heat flux would be a valuable tool for occupational and environmental physiology. General physiological factors as well as environmental factors have been used to build models which predict tolerance and heat storage (Cheung et al. 2000; Kim et al. 2013; Wang et al. 2011), however very few attempts at individual profiling have been published (Koscheyev et al. 2002). Predictive models are valuable when physiological responses cannot be monitored in real time, however, the validity of predictive models when used with work cycles and with cooling countermeasures requires further investigation (Kim et al. 2013).

A combination of profiling and modeling would be highly applicable to many situations which require active recovery during and between periods of work. With the knowledge and ability to measure many of the individual factors which contribute to heat flux (particularly in UHS) profiling could be integrated with predictive systems. At the very least a more detailed knowledge about individual heat flux, tolerance and optimal recovery would allow individuals to be make better decisions regarding safe time on task.

Microclimate control systems which account for individual profiles and variation in heat balance are already a topic of interest (Flouris and Cheung 2006; Koscheyev et al. 2002). Microclimate equipment that can react to real-time physiology is another way to address individual responses. A limitation to this novel individual approach is that the integration of many specialized technologies are complex, and potentially cumbersome and expensive (Flouris and Cheung 2006; Warpeha 2010). As complexity increases robustness tends to decrease which is not ideal in emergency situations.

A.7 Conclusions about Active Head Cooling

Active head cooling can offset hyperthermia, fatigue, and exhaustion through both physiological and perceptual effects and has the potential to improve recovery and reduce physiological strain during exercise.

Out of all of the studies to include exercise and active head cooling Shvartz (1970), Nunneley et al. (1971) and Palmer et al (2001) demonstrated the ability to actually lower core temperatures during exercise. All of these studies used a water perfused cooling hood. Rasch et al. (1991) demonstrated the ability of the head to function as a heat sink as long as latent/evaporative heat loss is preserved. Pretorius et al. (2010) demonstrated that whole head immersion could lower esophageal temperatures. When using water perfused cooling hood the neck, dorsum and sides of the head are cooled in a similar fashion to immersion while the face maintains evaporative and convective heat loss with the ambient environment. Perhaps the hood cooling can provide whole head cooling with fewer encumbrances than immersion? Cooling hoods might also compromise between active head cooling and maintenance of evaporative face cooling.

A.8 Active Cooling Countermeasures and Firefighting

Hand cooling after exercise in FPE, first demonstrated the potential of cooling countermeasures (Livingston and Nolan, 1989; House, 1994). This pathway accessed the venous anastomoses and returned cooled blood directly to the body core. Carter et al. (1999) later demonstrated that whole body fanning could alleviate cardiovascular strain between exercise periods in FPE.

This pathway enhanced convective air movement and enhanced evaporative cooling across skin surfaces.

Carter et al. (1999) did not prevent a rise in rectal temperature (T_r) but they did significantly attenuate the rise in T_r (0.25°C vs. 0.90°C in a control condition). Whole body fanning also significantly reduced heart rate (HR) responses during cooling and during subsequent exercise. This early research demonstrated that practical cooling countermeasures are worthwhile between exercise periods in FPE (Livingston and Nolan 1989; House, 1994; Carter et al., 1999).

More recently, Selkirk et al. (2004) found that hand and forearm submersion (FS) in cold water (17°C) had the greatest effect on core temperature and tolerance time when compared to passive cooling (PC) and fan misting (M). Mean rectal and skin temperatures were initially increased (approximately 1.3°C) by 50 minutes of exercise in FPE. In the FS condition, during the first 30 minute cooling period, rectal temperatures were significantly reduced (0.35 ± 0.2°C $p < 0.05$). Rectal temperatures remained significantly lower than the PC trial for the remainder of that cooling period and into the subsequent exercise period. Overall tolerance time (work time + cooling time) was significantly prolonged in the FS condition. Misting, although not as successful, also significantly reduced core temperature and increased tolerance time. The advantage of FS over M was that FS prolonged exercise to a greater degree and led to volitional exhaustion at lower core temperatures. Forearm submersion was superior at reducing thermal strain.

Giesbrecht et al. (2007) identified two other characteristics of hand (H) or forearm (FS) submersion as a cooling technique. Firstly, submersion removed more heat in colder water (10°C vs. 20°C); and secondly, submersion of both the hands and forearms lowered core temperature more than hand only immersion. Mean aural canal temperatures during FS and H in 10°C water were significantly lower when compared to passive cooling. This protocol consisted of three 20 minute periods of exercise in FPE interspersed with three 20 minute periods of cooling.

Hostler et al. (2010) found no difference amongst four ACDs and passive cooling when applied to recovery in a temperate (24°C) environment. Building on the exercise protocol used by Selkirk et al. (2004) subjects completed two 50 minute low intensity periods exercise separated by a 20 minute recovery intervention. Although not statistically significantly different an infusion of 4°C saline had the greatest effect on temperature reduction during recovery. These authors indicated that a major limitation to this cooling method was that the volume of saline was matched to the fluid loss of each subject. If a standard volume were used saline injection might have had a greater effect. A contraindication of saline infusions was the extreme discomfort noted by subjects upon injection. Unlike Selkirk et al. (2004) forearm submersion did not reduce core temperature or extend tolerance time any more than passive cooling, owing perhaps to the availability of a temperate ambient environment. Hostler et al. (2010) recommended that the available recovery environment be considered before the investment in active cooling devices.

Barr et al. (2009) combined FS and ice vest cooling to reduce core temperatures and lower HR. After 20 minutes of treadmill walking in FPE (5 km·h^{-1}; 3.11 mph and a 7 % grade), 15 minutes of FS recovery in a temperate environment (18°C) resulted in a significantly lower (0.5°C) core temperature and heart rate (approximately 18 beats·min^{-1}). In follow up work, Barr et al. (2011) found that the ice vest actually contributed very little to decreases in core temperature and HR. Their conclusion was that FS alone had the same effect as combining FS and ice vest cooling. Forearm submersion capitalizes on blood flow through the venous anastomoses which lead directly to the body core. The Ice vest relies on conduction from the vest through the torso. Barr et al. (2011) speculated that direct conduction was a poorer pathway for heat extraction. This limitation reinforces the importance of targeting anatomical and physiological pathways with the greatest effect on core temperature. In agreement with the hood cooling work of Nunneley et al. (1971), cooling technologies must also avoid skin vasoconstriction which reduces circulation and the potential for cooling.

Most recently Kim et al. (2011a) investigated the effects of two different liquid cooled garments (LCG) on the recovery and performance of subjects in FPE. Subjects wore two different styles of LCG underneath their FPE: a top cooling garment (TCG) which covered the head and forearms, and a short cooling garment (SCG) which covered the head, torso, forearms and thighs. Both garments significantly reduced mean HR during recovery but only the SCG significantly lowered HR and core temperature during exercise. The protocol consisted of three intermittent exercise periods walking in FPE at 70 % VO_{2max}, each separated by 10 minutes of recovery. Exercises periods were ended after 15 minutes or if 90 % HR_{max} was reached. Whether the cooling was applied during exercise and recovery, only during exercise or only during recovery is unclear. Both LCGs were circulating water at a temperature of 18°C and flow rates of 0.2 and 0.65 $kg \cdot min^{-1}$ within the TCG and SCG respectively. The ambient conditions were 35°C and a RH of 50 %. This protocol and these conditions resulted in a steady climb in core temperatures. However, only certain individuals' core temperatures dropped during recovery - illustrating individual differences in response to cooling. These authors concluded that passive cooling does not provide adequate recovery but that exercise and recovery with LCGs appear to be a useful countermeasure.

Several recent studies have used live fire drills and overlapping countermeasures (rehydration and cooling) to evaluate the validity of active recovery strategies in more operational settings. They have each upheld the need for recovery cycles but not all have supported the need for active cooling devices.

Carter et al. (2007) found that 20 minutes of FS in 12.5°C did not significantly reduce core temperature when recovery cooling took place in a cool ambient environment (15°C). The rate of cooling during the initial five minutes was greater with FS but this did not impact the mean result. Cooling was proceeded by 35 - 40 minutes of live fire drills. Carter et al. (2007) summarized that the lack of significant difference may have been due to the efficacy of passive cooling and de-encapsulation in a cool and dry environment. Other confounding factors may have been the consumption of 1 L of cool water, peripheral vasoconstriction and the lack of circulating water supply. The authors did not disregard FS as a countermeasure but they asserted that active cooling may not be necessary where cool and dry passive cooling is available.

In a research report prepared for the Orange County Fire Authority, ACDs, proper rehydration and maintenance of fitness were each factors which improved simulated firefighting drills and recovery (Espinosa N. 2007). Cooling countermeasures were applied for 20 min after completing two fifteen minute live fire drills. Among a sample of 17 subjects, randomly assigned from the pool of 101 participants, FS reduced core temperature by 0.68°C. Second to FS, the application of towels soaked in ice water reduced core temperature by 0.66°C. Misting and passive cooling reduced core temperature by 0.49°C and 0.42°C respectively. Core temperature was measured by ingestible capsule and compared to tympanic temperature during recovery. A comparison of core (ingestible pill) and tympanic temperatures demonstrated that tympanic temperature underestimated core readings by 0.8 – 1.8°C and did not detect the overshoot in core temperature observed during the initial minutes of recovery. Environmental conditions during recovery were hot (29°C) and humid (46 % R.H.) which are similar to the conditions of Selkirk et al. (2004) who also reported the significant effect of ACDs.

Colburn et al. (2011) also used a live fire drill and found that neither FS nor cooling vests were able to significantly reduce core temperature compared to a control. The live fire drills and recovery were each 20 minutes in duration. The control condition with passive cooling took place in an air conditioned trailer (ambient temperature 22.2 ± 0.6°C). The active cooling devices (FS in 20.9°C water and an ice cooling vests) were applied in a shaded recovery area (ambient temperature 22.5 ± 2.9°C). Inter-individual differences and lack of statistical power may have contributed to some of the non-significant comparisons; however, like Carter et al. (2007) cool and dry environments appeared to limit the potential of ACD when de-encapsulation and passive cooling are available.

Horn et al. (2011) found no difference between active and passive recovery following live fire drills with 21 firefighters. Building on the research of Espinosa (2007) active cooling consisted of vigorously applied cold towels. Trials took place on two separate days and used a within-subject, repeated measures design with multivariate statistical analyses. Each day began with 18 minutes of live fire drills then, after seven minutes of debriefing, subjects were randomly assigned in a counterbalanced way to one of the two recovery conditions. Both recovery conditions were 15 minutes in duration and required the removal of the entire FPE. Passive cooling took place in a 20°C environment with rehydration ad libitum. Active cooling took place in a similar environment and was combined with ad libitum water and the ingestion of 2 types of commercial beverage. These authors noted the trend of evidence which does not support use of ACDs when passive cooling in cool and dry environment is possible (Selkirk et al. 2004, Hostler et al. 2010, Espinosa N. 2007, Horn et al. 2011). A limitation of this study is that subsequent performance was only measured with a dummy drag task which lasted less than 1 minute. None of the studies to use live fire drills have also incorporated repeated cycles of work and active or passive recovery.

Active cooling devices and de-encapsulation may have the same effect in a cool and dry environment. Many of the laboratory studies to demonstrate significant effects have used hot and humid environments. The possibility of removing FPE and recovering in cool and dry conditions (available seasonally or with air conditioned vehicles), may mitigate the need for active cooling devices. These recent studies were conducted with a variety of experimental protocols and with overlapping countermeasures (for instance cool water ingestion and FS). Using de-encapsulation and passive cooling to lower core temperature when cool dry conditions are available is an important consideration before widespread operationalization of ACDs.

The attempt of these studies to use live fire tasks and more applied intervention conditions is an appropriate direction for future studies. Larger sample sizes and more consistent methods will be important in order to clarify the role of ACDs due to the variety of operational environments. Based on the strength of laboratory studies active cooling devices will reduce physiological strain and increase exercise tolerance when recovery takes place in hot humid conditions where passive cooling cannot be achieved.

A.9 Physiological and Operational Consideration

Several guidelines were outlined by Selkirk and McLellan. (2005) to deliver forearm submersion (FS), the most successful active cooling countermeasure they studied. These guidelines are useful to consider when establishing a frame work to evaluate other active cooling countermeasures.

The guidelines were to:

1. Remove the SCBA and FPE.
2. Maximize the exposure time to cooling (10 minutes to achieve two-thirds the benefit of 20 minutes).
3. To control the water temperature (where hose water 18°C is available but where cooler water will remove more heat).
4. To increase the frequency of cooling interventions as total work time increased.

Examining cooling countermeasures was a topic addressed in the review by Cheung et al. (2010) who were mindful of the following operational obstacles:

1. That safety of countermeasures when deployed in firefighting environments.
2. That integration of countermeasures into current equipment without compromising portability, ergonomics and freedom of movement.
3. That the opportunity to deploy countermeasures may be brief and cannot be easily preplanned.
4. That the location and environment of deployment is highly variable.

A combination of these two sources (Selkirk and McLellan. 2005, Cheung et al. 2010) yields a reasonable list of physiological and operational factors which can be used to evaluate active cooling countermeasures.

Important physiological factors to acknowledge are:

1. The heat transfer pathway must be intact given the ambient conditions (For example, overcooling and vasoconstriction must be avoided and the medium, such as water immersion, should have a greater capacity to remove heat than the maximum evaporative capacity of the environment).
2. The thermal gradient should be maximized.
3. Anatomical site selection should maximize body surface area (BSA) and sites of dense skin vascularization (Venous anastomoses, non-glabrous skin surfaces).
4. Cooling time and frequency should be sufficient to prevent or significantly retard the rise in core temperature.

Important operational factors to acknowledge are:

1. The targeted body surface should be quickly and safely accessible during the work or recovery phases of deployment.

2. The cooling countermeasure should significantly reduce strain in a time effective way.
3. The cooling countermeasure should be simple to use, transportable and easily maintained at a hazardous scene. Power requirements, bulk and durability must each be accounted for.

Even though heat stress is a danger when working in uncompensable heat stress health and safety must be considered along with physiological and operational variables. The health and safety factors listed below should also be considered:

1. The cooling countermeasure should be sanitary and accessible to multiple individuals who may be sharing or exchanging the device during duty rotations.
2. The cooling countermeasure should not burden the user. (devices should not cause more fatigue than they alleviate)
3. The physiological recovery from the countermeasure should match or exceed favourable perceptual responses.

During research studies the ratio of investigators to subjects is usually high however, this is the reverse in the field where multiple firefighters are monitored by a fewer number of medics. Some of the sanitary laboratory conditions which make cooling countermeasures relatively simple to implement in a laboratory might not be feasible in the field. Forearm submersion is a countermeasure which has repeatedly demonstrated the ability to increase tolerance time and reduce physiological strain (Selkirk et al. 2004, Giesbrecht et al. 2007, Barr et al. 2011) but the use of communal hydrotherapies carries the risk of infection and disease (Chapuis et al., 2004). Cold saline injections, another efficacious cooling countermeasure, would similarly require clean spaces and specialized care not always easily available during emergency response.

Studies demonstrating the cooling capacity of ice vests and tube line suits must address the issue of encumbrance. Adding layers to an already heavily layered protective ensemble will decrease movement economy and add to the metabolic cost of work. Adding additional mass decreases the functional relative VO_2. Both of these encumbrances will speed the onset of fatigue as well as increase the generation of metabolic heat.

The active cooling strategy of misting studied by Selkirk et al., (2004) is relevant to the perceptual versus physiological responses to certain countermeasures. During their investigation a misting strategy was able to increase work time but it also increased the number of subjects who reached the end criteria of core temperatures in excess of 39.5°C (7 of 15 compared to only 2 of 15 with forearm submersion). Misting lowered core temperature during recovery but it resulted in longer exposure times to a greater amount of physiological strain (higher core temperature and heart rate). Lee et al., (2012) found that the topical use application of 0.8 % menthol can significantly reduce the perceived stress while significantly increasing thermal strain. When administered to various skin sites, wearing both shorts and a t-shirt or wearing FPE, skin vasoconstriction was altered in a way that directly worsened the effect of UHS. Skin sweat rates decreased, resulting in greater rates of heat gain and in higher absolute core temperatures after 30 minutes of exercise.

Tikuisis et al. (2002) found that trained individuals potentially under-predicted physiological strain when perceived indices of thermal strain were used. The untrained group had better correlated physiological and psychological strain. Tikuisis et al. (2002) concluded that underestimation could result in a greater risk of exhaustion during prolonged (60 min) exercise in UHS. Trained individuals might have been better adapted to tolerate higher core temperatures at exhaustion. A countermeasure which uncouples the relationship between perceptual feedback and physiological impact could result in increased tolerance at the expense of safety.

Barr et al. (2011) demonstrated the overuse of countermeasures where the addition of an ice vest to FS offered no significant advantage. There are examples of successful combined techniques such as adding lower body negative pressure to cyclical recovery to enhance evaporative heat loss (Kenny and Gagnon 2010). The potential summative effects of tandem countermeasures should be pursued in future research, where two or more cooling countermeasures are operationally and physiologically applicable.

A.10 Heat Strain, Thermal Hyperpnea and Operational Countermeasures in Firefighting

Countermeasures which prevent physiological strain, injury and death, must keep pace with firefighting equipment which can prolong time on task (Schaeffer 2011). Work and recovery cycles can be used to reduce physiological strain. Cooling countermeasures can enhance recovery. Cooling countermeasures have demonstrated the ability to decrease heat stress and cardiovascular stress. Decreasing heat stress might also reduce ventilation and breathing stress, therefore, the impact of cooling countermeasures is potentially threefold. Heart attacks, heat stroke and asphyxiation are all recurring causes of hospitalization and death amongst firefighters. Schaeffer (2011) recommends implementing recovery cycles as the most important rule of air management which is also the most common rehabilitation for heat removal. The best cooling countermeasures may add to air management and decrease acute physiological strain.

A.11 Summary

There are multiple triggers which can lead to fatigue and exhaustion and when cooling countermeasures are used to reduce core temperature, and thermal strain, the onset of fatigue may be delayed or prevented. Cooling hoods have both physiological and perceptual effects; therefore, active cranial cooling may be able to improve the recovery resulting from exercise while wearing FPE.

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Appendix B

Detailed Methods

B.1 Sampling

A convenience sample of healthy male subjects, familiarized with working with a fire protective ensemble and a self-contained breathing apparatus, was recruited from the University of Alberta Campus and Edmonton area. Because of the demanding nature of the exercise subjects who exercised regularly were selected. Contraindications to inclusion were determined by the use of several questionnaires, specifically the PAR-Q+ and physician screening for ingestion of the temperature capsule. This sampling method was similar to that of previous studies investigating the effects of exercise in FPE (Nelson et al. 2009; Mayne et al. 2009).

B.2 Experimental Design

This experiment used repeated measures and a randomized crossover design. There were between three and five laboratory sessions depending on the experience of each subject and the success of the practice protocols. These sessions involved screening and a graded exercise test (GXT), a practice session and two experimental sessions. For volunteers inexperienced with work in fire protective ensembles (FPE) the purpose of the first session was to complete the consent and screening forms then to familiarize the subject with work in FPE. During a typical familiarization session the subject was taught how to operate and don the FPE and self-contained breathing apparatus (SCBA) then, while fully encapsulated, they were escorted while climbing stairs and walking at various grades on a treadmill. For experienced volunteers the purpose of the first session was to complete the consent and screening forms then to complete a GXT in FPE, breathing from the SCBA. The GXT became the second session for inexperienced volunteers after which there were no differences in protocols based on previous experience. Peak oxygen consumption ($VO_{2\ peak}$) was determined during the GXT and ventilatory threshold (VT) was measured to establish each individual's work rate for the practice session. Peak oxygen consumption was measured understanding that $VO_{2\ peak}$ is depressed approximately 17 % while using FPE and breathing from an SCBA (Dreger et al. 2006).

The purpose of the next session was to practice the experimental protocol and to ensure tolerance at the selected workload. When no adjustments to the practice session were made it was identical to the passive experimental session. None of the subjects required more than one practice session before a tolerable work rate just below VT was determined. The final two sessions were conducted in random order decided by the flip on a coin. All testing was conducted in the same laboratory with temperate ambient temperature (22°C) and low relative ambient humidity (5 %). Sessions were separated by at least 24 hours and each subject's sessions began at the same time of day to account for diurnal variations in body temperature (Kelly 2006; Edwards et al. 2002).

Five to seven hours before the practice and experimental sessions, a temperature transmitter (Jonah, VitalSense™, Mini Mitter, Bend, OR) was swallowed. Each subject kept the time of ingestion constant between trials in order to collect consistent core temperature (T_{core}) measures.

The subject arrived at the lab having abstained from caffeine and alcohol in the previous 12 hours and vigorous exercise in the previous 24 hours. The subjects supplied their own undergarments, socks and athletic shoes, and arrived at the lab clean shaven. Before measuring nude mass, each subject collected a midstream urine sample. The urine sample was immediately measured by hand held refractometer (PAL-10S, ATAGO® U.S.A, Bellevue, WA) to ensure the subject's USG was below $1.020\ g \cdot ml^{-1}$. Urine specific gravity was measured in the same way preceding the graded exercise test in order to give feedback to each subject on their hydration status which helped them to arrive properly hydrated for all remaining sessions.

After measuring nude mass and USG the subject donned a fire hall uniform (NFPA compliant pants and shirt). While seated, each subject was instrumented with a Polar™ heart rate transmitter, a snugly fitted blood pressure cuff on the right arm and a skin temperature sensor on the posterior right side of the neck next to the C7 vertebrae. The subject then sat quietly as five minutes. Baseline heart rate and blood pressure were measured each minute and the average after 5 minutes was recorded. Core and Skin temperatures were allowed to settle and were recorded at the end of the five minutes. These served as the baseline values for that day's trial.

After the baseline data was recorded the subject donned the fire protective ensemble (FPE) including a self-contained breathing apparatus (SCBA). Running shoes were worn instead of boots for the safety and comfort of the subjects. Before beginning exercise a total mass including all equipment and clothing was recorded then, before moving to the treadmill, grip strength and maximal inspiratory and expiratory pressure were also measured.

At the treadmill five additional minutes of seated measures were taken to establish baseline values for VO_2, $V_{ET}CO_2$, and V_E, This was immediately followed by a three minute warm up at half the grade to be used during the 20 minute exercise period.

B.3 Exercise protocols

B.3.1 Graded Exercise Test

The graded exercise test took place at a walking speed of 93.9 $m\cdot min^{-1}$ (3.5 $miles\cdot hr^{-1}$) on a motorized treadmill. The test began at a level grade (0 %) and was increased two percent every two minutes until ventilatory threshold (VT) was confirmed with the systematic increase in V_E/VO_2 ratio, while V_E/VCO_2 stayed constant or increased slightly (Wasserman 1987). After VT was confirmed, grade was increased two percent every minute until volitional exhaustion. The highest 20s VO_2 value was accepted as VO_{2peak} and the VO_2 at VT was expressed as the first 20s average where a clear change in the V_E/VO_2 could be observed.

B.3.2 Familiarization and Practice

Similar to Nelson et al. (2009) each subject completed a practice session replicating the experimental protocol to ensure that the exercise intensity, estimated from the GXT, was appropriate. If the exercise intensity was too difficult the grade was adjusted during the practice in order to complete the two 20 minute exercise durations. Generally, the grade had to be decreased by 0.5 % for every 5 minutes of work not completed. No subject required more than one practice session before a suitable exercise intensity was determined.

The tube lined cooling hood was introduced during all practice sessions. When adjustments were required during the practice session the hood was introduced during the final 10 minutes of the second recovery period. When no adjustments were required during the practice session the hood was introduced for 10 minutes after the completion of the second recovery period. When no adjustments were required the practice session was identical to the passive cooling session except for this familiarization with the hood.

B.3.3 Active and Passive Head Cooling Trials

Participants completed two-20 minute periods of walking at 93.9 $m \cdot min^{-1}$ (3.5 $miles \cdot hr^{-1}$) on a motorized treadmill at the grade just below that which elicited VT. Each exercise period was preceded by 3 minutes of warm-up walking at 93.9 $m \cdot min^{-1}$ and half the grade to be used during the 20 minutes of work. During the warm-up the subject was breathing from the SCBA and expired air was analyzed with the metabolic cart. At the completion of the exercise period three minutes of cool down took place walking at 67.03 $m \cdot min^{-1}$ (2.5 $miles \cdot hr^{-1}$) and 0 % grade. During the cool down the subject continued to breathe using the SCBA but the expired air was not analyzed by the metabolic cart. The cool down was immediately followed by the measurement of handgrip strength and maximal inspiratory and expiratory pressure.

A 20 minute period of seated recovery followed each exercise period. Transition time was recorded starting after the cool down until the start of seated recovery. Transition time was also recorded from the end of the seated recovery until the start of the second exercise warm up period.

During the recovery periods subjects were allowed a towel to wipe sweat from their face. Upon request, subjects were allowed to swill but not swallow a small amount of room temperature water.

B.4 Recovery

B.4.1 Passive Head Cooling

Passive head cooling took place while seated and at rest. In order to account primarily for the effect of heat loss from the head the SCBA, mask and flash hood were removed but the FPE jacket, pants and gloves were not. This is different from previous studies which allowed for the removal of the FPE jacket (Carter 1999; Selkirk et al. 2004; Barr et al. 2011).

B.4.2 Active Head Cooling with a Water-Perfused Hood

During active cooling the subject wore a high density tube-lined hood (Allan VanGaurd Technologies, Ottawa, ON, Canada). The hood was made from 50 % Kermel® and 50 % Viscose® fabric and had 4.6 m of tygon® tubing woven into its interior. Water was circulated to and from an insulated reservoir with 3 metres of insulated hose. Cooling hoods should be fitted to maximize the contact between the tubing and the skin. A compression garment (Nylon hosiery) was applied to improve fit and a dry flash hood was applied to insulate the cooling hood.

B.5 Heat Extraction and Water Temperature

The temperature of 10°C (inlet) was maintained by adding icy slush as required to an insulated water circulating tank (VERSA COOL 1105653, Med-Eng Systems Inc. Ottawa, ON). Ingoing and outgoing water temperature was measured by inline thermistors 30 cm from the hood. Before the start of each active cooling trial the two thermistors were run in series to compare their accuracy and to calculate a correction factor if required. Gross heat extraction was calculated based on the difference between the ingoing and outgoing water temperatures, the flow rate and the specific heat capacity and density of 10°C water. Net heat extraction was calculated by subtracting from the gross heat extraction the heat gain from the environment. Preceding trials were conducted with a Styrofoam head cooled in an identical way to the active cooling trial. Once the temperature of the Styrofoam head stabilized the mean temperature difference during 20 minutes of cooling was used as the value of heat gain from the environment.

Flow rate of the system ($320\ \text{ml}\cdot\text{min}^{-1}$) was established as the mean volume of water returned to the tank over repeated 30 second and 60 second intervals. This flow rate was verified on several different days. Colder water temperatures of 1°C (Palmer et al. 2001) and 5°C (Shvartz 1970; Nunneley and Maldonado 1983) have been used for head cooling but rapidly cooled skin can cause vasoconstriction which decreases the convective potential of blood flow. The selected temperature of 10°C was chosen to avoid skin vasoconstriction (Kurz et al. 1995).

B.6 Change in Body Mass

Mass was measured at the commencement of the protocol while wearing a dry pair of shorts. Nude mass was then calculated based on total mass minus the mass of the shorts. Final nude mass was measured at least 10 minutes after the end of the second recovery, in the same dry pair of shorts. On two occasions subjects with USG > 1.020 (1.021 and 1.026) were given 250 ml of warm water just after the 5 minute seated baseline measures when this occurred 0.250 kg was added to their initial nude mass and core temperature was monitored for an additional 5 minutes to insured the ingestion of water had no effect on core temperature measurements.

B.7 Clothing

B.7.1 Fire Protective Ensemble and the Self Contained Breathing Apparatus

National Fire Protection Association (NFPA) standard 1500 compliant clothing was used. There are slight modifications to the FPE to allow access, through a Velcro® sealed port, to the arm for blood pressure measurements (Mayne et al. 2009). The port remained closed except during the transitions when the blood pressure cuff was attached to a digital monitor. The mean mass of the FPE and SCBA was 22.5 ± 0.5 kg. The FPE included: pants; a jacket; a helmet; a face piece (mask); a flash hood; gloves and the SCBA. The SCBA consisted of a positive pressure regulator (Scott E-Z FLO), connected to a Scott pressure-reducing regulator, attached to a Scott 4.5 Air-Pak cylinder (Scott Safety, Monroe, NC, USA) worn as part of shoulder and waist supported back harness (Nelson et al. 2009). Running shoes were substituted for firefighting boots for the safety and comfort of the subject during exercise on the treadmill (Nelson et al. 2009).

B.7.2 Undergarments

Each subject supplied his own underwear, socks, and shoes. NFPA compliant, Edmonton fire rescue service uniforms were worn underneath the FPE, consisting of pants and a short sleeve shirt (55 % Fibrous fire retardant fiber, 45 % cotton, Lion Apparel, Dayton, OH).

B.8 Respiratory Gas Exchange

Expired gases were collected through the SCBA mask and regulator which was fitted with a Plexiglas® cone over its exhalation ports (Eves et al. 2002). Special attention was given to ensure a tight seal of the mask around the face to avoid leakage. The distal end of the cone was connected by hose to a ParvoMedics TrueOne™ 2400 metabolic measurement cart (MMC). Expired gas from the breathing apparatus was continuously measured and gas exchange variables were averaged every 20 seconds during the GXT and every 60 seconds during the practice and experimental trials. Flow calibration was performed before each use using a 3 L syringe. Gas analyzer calibration was performed immediately prior to and verified immediately following each exercise period using calibration gases (nominally 16 % O_2 and 4 % CO_2).

The partial pressure of end tidal carbon dioxide ($P_{ET}CO_2$) was sampled separately by a pump, sensor and CO_2 analyzer (AEI technologies Naperville, IL, Model, model R-1 pump, model P-61B sensor and model CD-3A carbon dioxide analyzer). The pump was turned on and allowed to sample for 30 seconds before any measurements were taken. Sampling was timed to avoid interfering with the verbal responses of subjects to perceptual scales. Expirations were collected through a sample line and filters from the SCBA cone immediately adjacent to the respirator exhaust ports. The percentage of expired CO_2 was observed for each breath on a real time digital display and the highest end tidal value was manually recorded. The mean of ten breaths within the same minute was recorded every 5 minutes during exercise. Gas analyzer calibration was performed immediately prior to each exercise period (nominal calibration gases were 4 % CO_2 from a standardized calibration bottle and 0.02 % CO_2 from room air. It was observed that the calibration of CO_2 values varied by up to 0.1 % after each exercise period, this may have been the result of humidity in the system.

B.9 Heart Rate and Blood Pressure

Heart rate was displayed every five seconds and recorded every 60 s during all conditions using a Polar™ heart rate monitor (FS1 receiver and T-31 transmitter; Polar Electro Canada, Lachine, QC, Canada). During baseline, blood pressure was measured every minute with an automated system while the subject remained still and silent (BpTRU™ Vital Signs Monitor BPM-100, Coquitlam, BC). Blood pressure was recorded every 5 minutes during recovery. A second measurement was taken if there was a HR discrepancy between the Polar™ and BpTRU™ systems.

B.10 Body Temperature

During the experimental trials skin and core temperature readings were capable of being measured every 10 s by a digital receiver (VitalSense™, VSM-100, Mini Mitter, Bend, OR). Due to the interference of multiple clothing layers occasionally data packets were not received as frequently but temperatures were successfully recorded every 5 minutes during exercise and recovery periods. Two receivers were used for most trials. One was placed in a jacket pocket to continuously receive and store data and the second was held by the investigator to observe and record temperatures in real time. After each trial both monitors were downloaded to a computer and on occasions when real-time temperature readings were missed the time stamped-data could be recovered.

Core temperature was measured telemetrically with a Jonah ingestible capsule (VitalSense™, Mini Mitter, Bend, OR). Gastrointestinal pill temperature is acknowledged to be a poor reflection of core body temperature when cool fluids are regularly ingested (Wilkinson et al., 2008) thus fluids ingestion was restricted during all trials. The ingestible capsule was swallowed between 5 and 7 hours before experimental trials. Standardizing the ingestion time provided core temperature data which should be in agreement with rectal temperature or esophageal temperature, as previously reported (O’Brien et al., 1998). Upon activation and before ingestion the telemetry from each capsule was observed to confirm it was sensitive enough to adjust to ambient conditions. Typically each capsule was allowed to sit next to a thermometer and a weather station, after 5 minutes each was checked to verify congruence between these measures of ambient temperature.

Neck skin temperature was measured on the posterior, right side of the cervical vertebrae just above the base of the neck, by a dermal patch (VitalSense™, Mini Mitter, Bend, OR). Application of the patch took place before the initial seated baseline measures. In most cases patches were able to be reused for the same subject on different trial days.

B.10.1 The Validity and Reliability of Intestinal Temperature

This study required a standardized interval of ingestion and limited the consumption of water to ensure the validity and reliability of using an ingestible temperature sensor. O'Brien et al. (1998) found that intestinal temperature (T_i) measured by ingestible capsule was between the “gold standard” of rectal (T_r) and esophageal (T_e) instruments (n = 9, 4 male and 5 female). They used a three hour protocol which manipulated core temperature to either increase or decrease and followed it with cycling at 50 % VO_{2peak}. Their analysis showed that T_i was a valid measurement. Some discrepancy between T_r and T_e were expected based on previous research but T_i was within the same margin of difference when compared to either T_r or T_e. The interval from ingestion to measurement was ten to twelve hour, further research to investigate the effect of lengthening or shortening that interval was suggested.

Gant et al. (2006) found good validity and reliability while measuring T_i and T_r during a multistage shuttle test (n = 10 males). The first trial confirmed that the systematic bias between T_i and T_r was acceptable (-0.15°C with 95 % confidence intervals from -0.02 to 0.05). The second trial confirmed that the day to day repeatability in T_i measurement was negligible (0.01°C, 95 % CI between 0.02°C and 0.05°C). The interval from ingestion to measurement was ten hours. The authors determined that T_i was an acceptable measure of core temperature applicable to field studies and within subject repeated measures designs.

Goodman et al. (2009) investigated the effects of timing on the reliability of T_i and found that two sensors ingested at different times did not always measure the same temperature (n = 8, 6 male and 2 female). The measurements obtained from two ingestible sensors varied by more than 0.25°C, 44 % of the time. The 0.25°C meaningful threshold of acceptance was determined based on previous records of individual variability (Consolazio et al. 1963). The sensors were ingested either five hours before or 29 hours before measurements were taken. Four subjects were excluded due to passing a sensor in less than 29 hours and one subject was excluded when fluid intake affected the sensor. These authors cautioned that the reliability of T_i was significantly affected by sensory ingestion timing and recommended a minimum interval of five hours, or preferably ten hours, precede temperature measurement (Goodman et al. 2009).

B.11 Perceptual Responses

At two minute intervals during the GXT and at five minute intervals during each exercise period, the subject was asked to indicate a numerical rating of exercise stress, breathing stress and thermal stress.

Perceptual responses were measured on scales modified from other sources to produce simple 10 point arrangements while preserving the written designations used by earlier scales (Borg 1982; Tikuisis et al. 2002). Each scale was arranged vertically, in a top down ascending numerical order. Each scale was continuously displayed on large poster paper in front of the subject and oral responses were recorded at each time point. After data collection each scale was correlated to a corresponding physiological variable to measure the agreement between the two (Table C.14).

Perceived exercise and breathing stress (ES and BS) were presented as follows: 0 = "None at all" 1 = "Very very easy" 2 = "Very easy" 3 = "Easy"
4 = "Somewhat easy" 5 = "Moderate" 6 = "Somewhat hard" 7 = "Hard"
8 = " Very hard 9 = "Very very hard" 10 = "Maximal".

Perceived thermal stress of the body (TS) and head (TSH) were presented as follows: 0 = "Unbearably cold" 1 = "Very very cold" 2 = "Very cold" 3 = "Cold"
4 = "Cool" 5 = "Moderate" 6 = "Warm" 7 = "Hot" 8 = "Very hot"
9 = "Very very hot" 10 = "Unbearably hot".

Thermal stress and thermal stress of the head were also measured during the recovery periods. Specifically subjects were asked for "whole body" then "head only" responses.

B.12 Fluid Sampling

Upon arrival, each subject provided a mid-stream urine sample to be analyzed for urine specific gravity. Sweat loss was estimated based on changes in nude (dry) body mass (kg) as follows: sweat loss (ml) = body mass$_{pre}$ - body mass$_{post}$, understanding the limitations of this measure (Maughn et al. 2007).

B.13 Strength Measures

Grip strength was measured with the right hand using a handgrip dynamometer (JAMAR, Sammons Preston Rolyan, Bolingbrook, IL). The subject was familiarized with its use and had the dynamometer fitted to their hand during the GXT session. For consistency the subjects' hand was ungloved and dried before each measurement. The dynamometer was griped at the subjects' side in a neutral position then squeezed for 3 seconds each trial. The arm, hand and dynamometer were not allowed to make contact with the body or surrounding objects. Subjects followed each maximal effort by 15-20 seconds of rest. Two to three trials were required to obtain a maximal value and another trial within 2 kg of the subject’s best effort. The mean of these two values was used.

Maximal inspiratory and expiratory pressure was measured to estimate respiratory muscle strength in a similar manner to Butcher et al. (2007). Subjects were familiarized with the measurement procedure during the GXT and practice trial. After initial coaching on consistency and effort the subjects were not allowed to view their results. The apparatus consisted of a mouthpiece connected to a rigid occluded tube with a small (1 mm) perforation to prevent facial muscle contribution. Pressure was recorded in centimetres of water (cmH_2O) by a positive/negative pressure gauge (Cole Parmer Co, Stratford, CT, USA). Both maneuvers were done standing with a quasi-isometric effort. The inspiratory maneuver was always done first and began at residual volume. The expiratory maneuver began at total lung capacity. These measurements took place immediately after measuring handgrip strength and were repeated until the two highest values were within 10 cmH_2O. The mean of these two values was recorded. To keep the transition time consistent between trials subjects were encouraged to complete these measures in three attempts. No more than 5 attempts were allowed in order to control the transition time.

Table B.1 A stepwise overview of the graded exercise test (GXT) protocol

Pre-Experiment Preparations

1. For a 24 hour period, avoidance of vigorous exercise.
2. For a 12 hour period, abstinence from alcohol and caffeine.
3. Arrival on time being properly hydrated and clean shaven.

Lab Preparations (approximately 30 minutes in duration)

4. Collection of a urine sample to measure specific gravity (USG).
5. Measurement of nude body mass and application of a heart rate (HR) monitor.
6. Donning of a fire hall uniform.
7. Application of a blood pressure (BP) cuff.
8. Begin 5 minutes of seated rest and baseline measures.
9. HR and BP were recorded.
10. Donning of the FPE and SCBA.
11. Measurement of mass in FPE.
12. Measurement of handgrip strength and maximal inspiratory pressure (MIP) and maximal expiratory pressure (MEP).

Graded Exercise Test (approximately 20 minutes in duration).

13. Walking at 93.9 $m \cdot min^{-1}$ (3.5 $miles \cdot hr^{-1}$) and 0 % graded where grade was increased by 2 % every 2 minutes, while physiological and perceptual responses were measured (V_E, VO_2, VCO_2, HR, ES, BS, and TS).
14. Grade was increased by 2 % each minute once ventilatory threshold (VT) was confirmed by an increase in the V_E/VO_2 ratio.
15. The test was terminated at volitional exhaustion
16. Measurement of hand grip strength, MIP and MEP.

Final Measure

17. Measurement of dry nude body mass took place 10 minutes after completion.

Table B.2. A stepwise overview of the experimental protocol

Pre-Experiment Preparations

1. For a 24 hour period, avoidance of vigorous exercise.
2. For a 12 hour period, abstinence from alcohol and caffeine.
3. At a fixed time 5-7 hours in advance of arriving, ingestion of a temperature sensor.
4. Arrival on time being properly hydrated and clean shaven.

Lab Preparations (approximately 30 minutes in duration)

5. Collection of a urine sample to measure specific gravity (USG).
6. Measurement of nude body mass and application of a HR monitor.
7. Donning of a fire hall uniform.
8. Application of a neck sensor and BP cuff.
9. Begin 5 minutes of seated rest followed immediately by baseline measures.
10. HR, BP, and temperature were recorded.
11. Donning of the FPE and SCBA.
12. Measurement of mass in FPE.
13. Measurement of handgrip strength and maximal inspiratory pressure (MIP) and maximal expiratory pressure (MEP).

Experimental Conditions (approximately 100 minutes in duration)

14. Completion of a five minute seated baseline to measure, V_E, VO_2, and $P_{ET}CO_2$ in FPE.
15. Completion of a three minute warm up.
16. Completion of a 20 minute constant work period while measuring physiological and perceptual responses (V_E, VO_2, VCO_2, HR, temperature, ES, BS, TS).
17. Measurement of hand grip strength and maximal inspiratory and expiratory pressure (MIP, MEP).
18. Transition to the recovery area.

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19. Completion of an active or passive, 20 minute, seated recovery while measuring physiological and perceptual responses (HR, temperature, BP, TS, TSH).
20. Transition back to the treadmill.
21. Repetition of steps 15 thru 19.

Final Measure (approximately 20 minutes in duration).

22. Measurement of dry nude body mass took place 10 minutes after completion.

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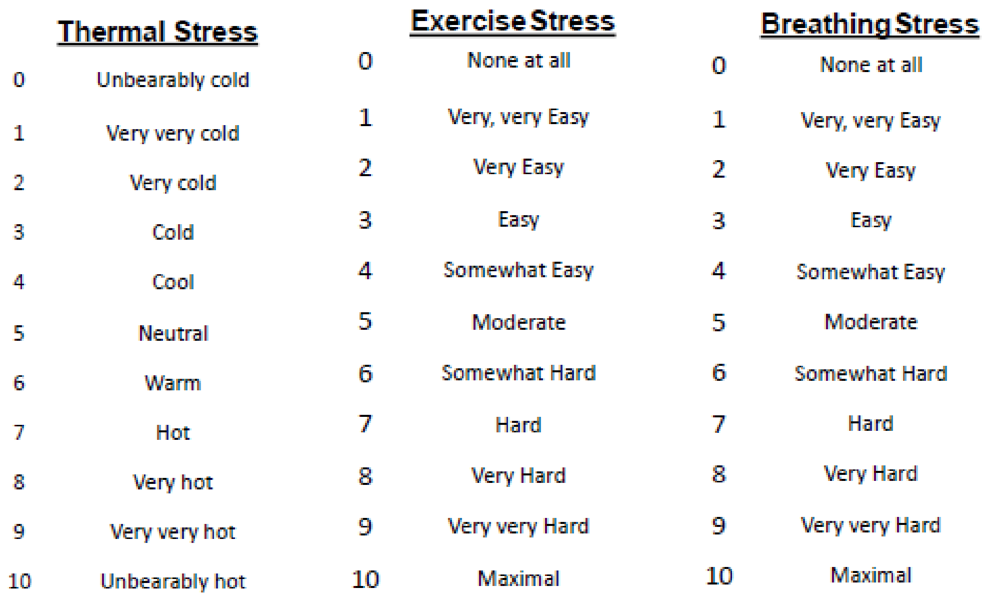
Appendix C

Additional Materials

C.1. Visual Analog Scales

The three psychometric scales developed and selected for this research are displayed below



	Thermal Stress		**Exercise Stress**		**Breathing Stress**
0	Unbearably cold	0	None at all	0	None at all
1	Very very cold	1	Very, very Easy	1	Very, very Easy
2	Very cold	2	Very Easy	2	Very Easy
3	Cold	3	Easy	3	Easy
4	Cool	4	Somewhat Easy	4	Somewhat Easy
5	Neutral	5	Moderate	5	Moderate
6	Warm	6	Somewhat Hard	6	Somewhat Hard
7	Hot	7	Hard	7	Hard
8	Very hot	8	Very Hard	8	Very Hard
9	Very very hot	9	Very very Hard	9	Very very Hard
10	Unbearably hot	10	Maximal	10	Maximal

These scales were developed to acquire ordinal level data. These scales afforded a simple 10 point selection which otherwise would have required switching between different scales each with its own range (see B.11 and Table C.14).

C.2. Additional Tables, Figures and Plates

Table C.1. Mean (± SD) subject characteristics (n = 12 males).

Age (years)	Height (cm)	Mass (kg)	BSA* (m^2)
28 ± 5	177.3 ± 6.5	75.85 ± 9.67	1.9 ± 0.1

* Du Bois and Du Bois 1989

Table C.2. Mean (± SD) oxygen consumption ($VO_{2\ peak}$), grade and ventilation ($V_{E\ peak}$) during the graded exercise test (n = 12).

	$VO_{2\ peak}$ ($L \cdot min^{-1}$)	$VO_{2\ peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	$Grade_{\ peak}$ (%)	$V_{E\ peak}$ ($L \cdot min^{-1}$)
Mean ± S.D	3.49 ± 0.50	46.2 ± 4.3	17.0 ± 2.6	136.6 ± 22.3
Range	1.66	14.0	10.0	84.0

Table C.3. Mean (± SD) body mass and urine specific gravity (USG) (n = 11).

	Pre-Mass (kg)	Post-Mass (kg)	Δ Mass (kg)	USG (U)
Active	75.22 ± 9.75	72.99 ± 9.10	2.2 ± 0.8	1.008 ± 0.005
Passive	75.48 ± 10.05	73.15 ± 9.48	2.4 ± 0.7	1.011 ± 0.007
p-value	0.24	0.46	0.19	0.19

Table C.4. Mean (± SD) baseline core temperature (T_{core}), neck skin temperature (T_{neck}), systolic (SYS), diastolic (DIA) and mean arterial pressure (MAP) and heart rate (HR) after five minutes of seated rest in pants and shirt (n = 12).

	T_{core} [a] (°C)	T_{neck} [a] (°C)	SYS (mmHg)	DIA (mmHg)	MAP (mmHg)	HR (bpm)
Active	37.0 ± 0.3	32.5 ± 1.1	104 ± 10	63 ± 12	76 ± 9	65 ± 11
Passive	37.0 ± 0.3	32.4 ± 1.4	104 ± 8	65 ± 8	78 ± 7	66 ± 10
p-value	0.91	0.74	0.93	0.39	0.27	0.60

[a] n = 11; [b] MAP = DIA + 1/3(SYS-DIA)

Table C.5. Mean (± SD) open circuit spirometry, before exercise period one, while seated and while wearing fire protective ensemble and self-contained breathing apparatus (n = 12).

	VO_2 (ml · kg^{-1} · min^{-1})	VO_2 (L · min^{-1})	V_E (L · min^{-1})
Active	4.3 ± 0.5	0.32 ± 0.05	11.0 ± 2.6
Passive	4.0 ± 0.6	0.30 ± 0.05	10.6 ± 2.1
Difference	0.2	0.02	0.4
p-value	0.21	0.22	0.57

Table C.6. Mean (± SD) oxygen consumption during two 20 min exercise (EX1 and EX2) periods (n = 12).

	VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)		VO_2 ($L \cdot min^{-1}$)		% $VO_{2\ peak}$ %	
	EX1	EX2	EX1	EX2	EX1	EX2
Active	29.6 ± 2.7	30.6 ± 3.1*	2.23 ± 0.29	2.30 ± 0.30*	65 ± 8	67 ± 9
Passive	29.8 ± 3.0	30.7 ± 3.0*	2.24 ± 0.26	2.32 ± 0.31*	65 ± 8	67 ± 9
p-value	0.972	0.965	0.918	0.732		

* Significantly different than EX1

Table C.7. Mean (± SD) perceived thermal stress at the end of each 20 min exercise (EX1 and EX2) or recovery (R1 and R2) period (n = 11).

	EX1	R1	EX2	R2
Active	7.5 ± 0.9 $^{Y, W}$	5.8 ± 0.9 $^{Z, X}$	8.0 ± 1.2 $^{Y, W}$	6.3 ± 0.9 $^{Z, X}$
Passive	7.6 ± 0.9 ^{YY}	6.6 ± 0.8 # $^{Z, X}$	8.3 ± 1.1 $^{Y, W}$	6.7 ± 1.1 # ^{X}
p-value	0.655	< 0.001	0.181	< 0.001

Significantly different than Active, $p < 0.001$.

^{Z} denotes significantly different than EX1, $p < 0.001$.

^{Y} denotes significantly different than R1 $p < 0.001$.

^{YY} denotes significantly different than R1, $p < 0.05$.

^{X} denotes significantly different than EX2, $p < 0.001$.

^{W} denotes significantly different than R2, $p < 0.001$.

Table C.8. Mean (± SD) perceived thermal stress of the head at the end of each 20 min recovery (R1 and R2) period (n = 11).

	R1	R2
Active	3.6 ± 1.0	3.6 ± 0.9
Passive	5.3 ± 1.0 #	5.6 ± 1.1#
p-value	< 0.001	< 0.001

Significantly different than Active

Table C.9. Mean (± SD) perceived breathing stress at the end of each 20 min exercise (EX1 and EX2) period (n = 11).

	EX 1	EX2
Active	6.6 ± 1.0	7.5 ± 1.1*
Passive	6.4 ± 1.1	7.7 ± 1.6*
p-value	0.409	0.409

*significantly different than EX1 p < 0.005

Table C.10. Mean (± SD) perceived exercise stress at the end of each 20 min exercise (EX1 and EX2) period (n = 11).

	EX 1	EX2
Active	6.9 ± 1.4	7.9 ± 1.2*
Passive	6.8 ± 1.1	8.0 ± 1.3*
p-value	0.635	0.635

*significantly different than EX1 $p < 0.001$

Table C.11. Mean (± SD) maximal inspiratory and expiratory pressures (MIP and MEP) and GRIP strength immediately before the first and immediately after the first and second exercise periods.

	PRE	EX1	EX2
Active			
MIP	138 ± 27	143 ± 33	141 ± 30
MEP	169 ± 32	169 ± 27	166 ± 29
GRIP	52 ± 10	50 ± 11*	50 ± 10*
Passive			
MIP	138 ± 28	143 ± 33	141 ± 30
MEP	170 ± 34	169 ± 27	160 ± 21
GRIP	53 ± 10	51 ± 10*	51 ± 11*#

*significantly different than PRE p < 0.01

significantly different than ACTIVE p < 0.05

Table C.12. Mean (± SD) transition times between periods not including warm up or cool down (n = 12).

	EX1 to R1 (min)	R1 to EX2 (min)	EX2 to R2 (min)
Active	6.1 ± 1.5	4.7 ± 1.3	5.7 ± 1.5
Passive	5.8 ± 2.6	4.9 ± 1.1	5.3 ± 1.1
Difference	0.3	0.1	0.5
p-value	0.53	0.75	0.30

Table C.13. Heat extraction from the ambient environment during 20 minutes of cooling. The tube lined hood was placed on a Styrofoam® head and covered with a compression garment and insulating flash hood.

Time (min)	Inlet (°C)	Outlet (°C)	Δ (°C)	Styrofoam Head Temperature (°C)
0 - 5	9.82 ± 0.16	10.18 ± 0.14	0.36 ± 0.04	13.12 ± 0.03
5 - 10	8.95 ± 0.24	9.32 ± 0.25	0.37 ± 0.05	13.36 ± 0.15
10 - 15	9.13 ± 0.15	9.48 ± 0.15	0.36 ± 0.01	13.55 ± 0.02
15 - 20	9.57 ± 0.14	9.91 ± 0.13	0.35 ± 0.01	13.48 ± 0.03
0 - 20	9.38 ± 0.37	9.74 ± 0.37	0.36 ± 0.03	13.38 ± 0.18

Table C.14. Pearson Correlations in relation to physiological and perceptual responses during exercise (EX1,EX2) or during recovery (R1,R2) in the following pairs, exercise stress (ES) and physiological strain index (PSI), breathing stress (BS) and minute ventilation (V_E), thermal stress of the head (TSH) and change in core temperature (ΔT_c), thermal stress (TS) and ΔT_c. Where a significant difference between conditions was found each condition was compared separately (n = 11).

Comparison	EX1,EX2	P value	R1,R2	P value
ES vs. PSI	r = 0.972	< 0.01		
BS vs. V_E	r = 0.996	< 0.01		< 0.01
Active TSH vs. ΔT_c			r = 0.797	< 0.05
Passive TSH vs. ΔT_c			r = 0.807	< 0.05
Active TS vs. ΔT_c	r = 0.856	< 0.01	r = 0.937	< 0.01
Passive TS vs. ΔT_c	r = 0.957	< 0.01	r = 0.804	< 0.05

		END			
		T1	**T2**	**T3**	**T4**
LEAD	**T1**		1.36	-1.75	-2.08
	T2	-1.41		-3.14	-3.44
	T3	1.65	2.94		-0.22
	T4	2.08	3.44	0.18	

Figure C.1. Temperature (°C) comparisons between four inline thermistors. In order to select those with the least difference four thermistors were arranged in paired series receiving water from the same source. The order (LEAD, END) was counterbalanced to compare and recheck each pairing. END was always subtracted from LEAD (LEAD – END). Notice that thermometer 4 (T4) and T3 were selected having the least difference. The difference between thermometers was checked prior to each trial and when a discrepancy was detected the heat extraction results were corrected.

Plate C.1 Passive cooling condition (displayed with access to the blood pressure cuff which was closed unless adjustment was required).


[redacted]

Plate C.2 Active cooling condition (the addition of the compression garment and flash hood had not yet occurred).


[redacted]

Plate C3. The reservoir and pump system used to circulate water.

Plate C.4 Tube lined hood, compression garment and flash hood.

Plate C.5 Hood and inline thermistor configuration.