Upper vs Whole Body Cooling During Exercise with Thermal Protective Clothing in the Heat

by

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CONTRIBUTION OF AUTHORS

The thesis is organized as a "sandwich" that chapters 3, containing material from journal article that awaiting publication. Following is the title of the prepared research article, and the authors' contributions of the thesis: Chapter 3 includes the content submited in the Aerospace Medicine and Human Performance manuscript titled “Upper vs Whole Body Cooling During Exercise with Thermal Protective Clothing in the Heat.”

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CHAPTER 1: INTRODUCTION

Significant heat stress is a common risk in various commercial, industrial, and military operations in the heat. In a world where temperatures can range from as high as 54°C in places like the United States, Africa, and the Middle East to as low as -89°C in the Antarctic, humans must deal with the difficulty of regulating their body core temperature to maintain homeostasis.[1]

It is crucial to prevent hyperthermia and heat illness among workers who are exposed to dangerous conditions with high environmental temperatures. A rise in body temperature can reduce work output, impair cognitive function and behavior, and increase the likelihood of accidents. [2] When performing heavy work in hot conditions, the body may experience a gradual buildup of heat if the effects of elevated metabolic heat production resulting from work, exercise, and high temperatures are not counteracted.[2]

Military personnel, firefighters, and other government employees who are engaged in high-risk missions wear individual protective gear to defend themselves. Despite the protective gear's direct contribution to field survival and decreased self-defence injury rates, it can reduce a person's ability to dissipate excess heat, which can increase susceptibility to increases in core temperature (T_{co}).[3] Protective gear reduces comfort and increases heat stress due to its low permeability, which limits heat exchange between the skin and the surrounding environment. Sweating is the primary way for the body to regulate temperature, but protective gear makes sweating less efficient, leading to thermal discomfort and decreased performance.[4] Evaluating the physiological and psychological strain of wearing protective gear is crucial to improving safety, comfort, and performance. Working in hot and humid environments while wearing impermeable or nonporous personal protective equipment significantly increases the risk of heat stress-related injuries[5] leading to overheating, especially when quick and accurate decision-making is necessary[6] Individual cooling systems can be a good solution to manage heat stress. There are several methods to control heat stress, such as engineering (physical changes to the environment or equipment to manage heat stress, like installing air conditioning or ventilation systems) and management controls (organizational policies and practices to prevent heat stress, such as scheduling work in cooler times, providing breaks in shaded areas, and ensuring access to water and training on heat-related illnesses), and one effective strategy is using personal cooling vests which absorb excess heat and provide thermal comfort in hot environments.[4]

Efforts are underway to develop effective personal cooling systems to remove excess body heat while working, especially in hot environments where wearing protective gear makes it harder to regulate body temperature. [7] The choice of cooling medium (e.g., ice, water, air, or phase change materials) should be based on the specific working conditions, and consider factors such as weight, mobility, and cooling efficiency. If carefully considered in the design process, any of these mediums can effectively dissipate heat from the human body.[7]

Selecting the right cooling system for a particular situation can be difficult as there is a vast array of options on the market, with selection mainly based on the manufacturers' product descriptions. Cooling vests can be classified into five categories based on their cooling method: air-cooled vests, liquid-cooled vests, evaporative cooling vests, phase change cooling vests, and hybrid (combination of 2 or 3 three types) cooling vests.[8] All the different vests have advantages and are effective in certain situations, but their effectiveness can be influenced by factors such as environmental conditions and costs. Furthermore, various studies have shown that their effectiveness varies.[9]

A Liquid Cooling Garment (LCG) is a popular form of cooling technology. It operates by using a liquid coolant, such as water or ethylene glycol, as the circulating fluid. The coolant is stored in a reservoir and circulated through a network of tubing inside the garment using external power, such as a battery-powered micropump.

There are several studies on the effectiveness of liquid cooling vests, and some have reported them as effective, while others have reported them as not effective.[10] These studies primarily examined vests that cover only the torso. Little work has been done on the effect of whole body cooling more than the upper body.

A specialized LCG that covered the head, torso, thighs, and lower arms was studied. [11] This garment was effective in decreasing the physiological and thermal heat strain (heart rate and core temperature) compared to a LCG that covered only the head and lower arms[11] or no cooling at all.[6] These results are not surprising because the specialized LCG had not only an increased surface area but also a threefold increase in flow rate. It is not known which body surface configurations would be more effective if the cooling power (e.g., the same liquid flow rate) is the same.

Koscheyev[12] cooled different body segments with 8°C water and demonstrated that cooling capacity for the upper body (5.18 kcal/min) was 56% higher than for the lower body (3.71 kcal/min) in resting subjects. Therefore, it might seem best to apply all cooling power to the upper body. However, if heavy leg exercise is involved, heat production and blood flow to the lower body will be proportionally greater, and redistributing some cooling to the lower body may be beneficial. Also, concentrating all cooling to a smaller total surface area (e.g., the upper body) my result in unacceptable cold discomfort.

The purpose of this study was to compare the efficacy of the same cooling power applied to either upper body or whole body cooling systems in reducing physiological and thermoregulatory stress, improving subjective responses, and enhancing cognitive function during exercise in a hot environment while wearing firefighter turnout gear. It was hypothesized that cooling would be beneficial and that whole body cooling would be more effective than upper body cooling.

CHAPTER 2: REVIEW OF LITERATURE

Thermoregulation

In humans, body temperature is made up of two different temperatures: core temperature and skin temperature (T_{sk}). T_{co} refers to the temperatures of the abdominal, thoracic, and cranial cavities, while T_{sk} refers to the temperatures of the skin, subcutaneous tissue, and muscles. The brain regulates T_{co} to be around 37°C during rest, whereas T_{sk} is influenced more by skin blood flow and environmental conditions and has an average temperature of around 33-34°C in a thermoneutral environment. When exposed to cold ambient temperature, T_{sk} decreases, but T_{co} may remain relatively constant. Although humans are homeotherms and able to maintain a constant temperature, the distinction between T_{co} and T_{sk} is unique in that T_{co} is endothermic and regulated by the brain, while T_{sk} is ectothermic and influenced by external factors.[13]

The regulation of human body temperature is controlled by the temperature regulation center located in the hypothalamus. Information regarding temperature levels is received by the hypothalamus from sensory receptors in the skin and various central structures such as the spinal cord and brain. This integrated thermal signal (ITS) triggers responses for either heat gain or heat loss, depending on whether the body is warm or cold[14] (Figure 1). When the body is warm (elevated ITS), heat loss mechanisms are activated, including vasodilation (increased blood flow to the skin for radiant heat loss) and sweating (evaporative heat loss from the skin or clothing). Conversely, when the body is cold (depressed ITS), heat loss is minimized through vasoconstriction (reduced blood flow to the skin) and heat production is increased via shivering, which involves involuntary muscle contractions generating heat.[15]

Figure 1. Heat gain and heat loss responses to ITS.

Solid lines represent sweating (red) and shivering (blue) intensity. Dashed lines represent vasodilation (red) and vasoconstriction (blue) intensity. As ITS deviates from normal values, response are initiated and increase to a maximum value. The Thermoneutral Zone is the range of ITS between thresholds for vasomotion (e.g., vasodilation to vasoconstriction) and the Null Zone (which is often referred to as the core temperature null zone) is actually the range of ITS between thresholds for sweating and shivering.

Each thermoregulatory response exhibits specific characteristics: 1) Threshold - the ITS level at which the response begins; 2) Gain - the relative increase in response for a given change in ITS; and 3) Maximum - the maximum intensity of the response. Various thermoregulation control models reflect the organization of behavioral choices and physiological responses.[16] The perception and onset of thermoregulatory responses are defined as follows: The "thermal comfort zone" refers to the ambient temperature range perceived as comfortable without eliciting behavioral changes. The "thermoneutral zone" is the range of ITS where core temperature (Tco) can be maintained solely through adjustments in skin blood flow. Lastly, the "core temperature null zone" represents the range of ITS between the thresholds for shivering and sweating. As depicted in Figure 1, the ITS range expands from the thermal comfort zone to the thermoneutral zone and finally to the null zone.

T_{co} represents the temperature of the blood in circulation, and the most reliable measure of T_{co} is the temperature of the blood in the pulmonary artery. The pulmonary artery receives deoxygenated blood from the right ventricle of the heart. After blood is oxygenated in the lungs, it returns to the heart through the pulmonary veins, entering the left atrium. From the left atrium, oxygenated blood is pumped into the left ventricle and then into the systemic circulation through the aorta. The aorta and its branches distribute oxygenated blood to various organs and tissues throughout the body. Heat distribution throughout the body is primarily regulated by the cardiovascular system in conjunction with other mechanisms such as vasodilation and vasoconstriction. The circulatory system helps regulate body temperature by redistributing heat generated by metabolism and external factors. Fluctuations in T_{co} can have a significant impact on the body's homeostasis since T_{co} reflects the amount of heat the cells and organs are exposed to in the circulation, abdominal, thoracic, and cranial cavities. Extreme changes in T_{co}, such as temperatures over 42°C, can harm cellular and organ functions and potentially threaten the survival of the individual.[15]

Hyperthermia can negatively affect the central nervous system, causing systemic inflammation, tissue death, and multiple organ failure. [13]The strong association between T_{co} and physiological homeostasis and disturbances makes T_{co} an important clinical and laboratory indicator of thermal strain in the body.[13]

Mechanisms of Heat Transfer

Heat transfer mechanisms can be divided into two broad categories: dry (conduction, convection, and radiation) and wet (evaporation). Dry heat exchange is dependent on temperature differences within the body (such as from the core to the periphery) and the environment. Conduction, convection, and radiation can result in heat being gained or lost in either direction as it moves from high temperature objects to lower temperature ones. However, evaporation only causes heat loss and can only happen in one direction. When a liquid transforms into a gas (like water or sweat evaporating), it takes energy to do so, and the heat is taken from the surface it occurs on, such as skin or clothing. Conductive heat transfer occurs when two objects that are in direct contact. Radiative heat transfer occurs through air or space using electromagnetic radiation to objects with a lower temperature. Convective heat transfer happens when air or water flows across the boundary layer, which is the area directly adjacent to the skin surface. By replacing the boundary layer with a warmer or cooler medium, heat transfer can be increased.[17]

The rate of blood flow to the skin, which transports heat from the core to the periphery, affects radiative heat exchange. Wet heat loss occurs through the evaporation of liquid, typically from sweat secreted by glands in the skin. The amount of evaporative heat loss depends primarily on the difference in water vapor pressure between the body surface and the environment, which can be affected by the environment, clothing, and changes in sweat gland activity and output.

As the body's temperature drops, blood vessels in the skin surface constrict, reducing blood flow to the skin's surface and limiting heat loss.[18] However, when the body's temperature starts to increase, the opposite process of vasodilation occurs. Blood vessels in the skin surface dilate, increasing blood flow to the skin's surface and facilitating heat transfer from the body to the environment. This process begins in the same regions where vasoconstriction is initiated, i.e., the extremities, and gradually spreads throughout the body. Therefore, the regions that lost heat first due to vasoconstriction will also gain heat first during vasodilation. Vasoconstriction and vasodilation are dynamic processes that help the body adapt to different temperature conditions. The regions that were conserving heat during vasoconstriction will indeed be the first to gain heat during vasodilation. This coordinate response is crucial for maintaining the body internal temperature within a narrow, optimal range.[18]

Heat Stress on Performance

Humans are homeothermic creatures, which means that they maintain a consistent body temperature throughout the day. When the body generates heat through increased metabolic activity, it activates mechanisms to dissipate the excess heat and maintain a steady temperature.[19] Heat balance is achieved when the amount of heat generated by the body or obtained from the surroundings is equal to the amount of heat lost from the body. During physical activity in warm conditions, the body may not be able to lose heat as quickly as it is produced. This leads to the accumulation of heat in the body, causing a rise in internal body temperature throughout the exercise, a condition known as uncompensable heat stress (UHS), which can reduce performance.[20]

When a person exercises in hot conditions, their body relies heavily on sweating to regulate body temperature. However, because sweating causes fluid loss, blood volume and stroke volume decrease, and plasma osmolality increases. To counteract these effects, it is necessary to replace the lost fluids by drinking water. Failure to do so can lead to hypohydration, which triggers a series of physiological responses, including an increased heart rate, that can ultimately harm athletic performance.[20] Dehydration leads to reduced blood volume, increasing heart rate and straining the cardiovascular system, resulting in decreased endurance and performance. Then, heat stress diverts blood away from muscles towards the skin for cooling, reducing oxygen and nutrient delivery to muscles, causing fatigue and reduced strength. Moreover, rising core body temperature impairs optimal performance and can lead to heat-related illnesses. Heat stress also impairs cognitive functions, affecting concentration and decision-making, crucial for tasks like operating machinery or sports. Finally, sweating during heat stress leads to electrolyte loss, causing muscle cramps, weakness, and spasms and heat-related illnesses.[21]

Moreover, heat stress is a significant factor that impacts performance levels, particularly in many occupations where it is a major concern. When the working environment is hot, it can have negative effects on the human body.[20] These can range from mild symptoms like heat rash, muscle cramps, and fatigue to severe consequences for various organ systems, ultimately leading to heat stroke, which can be fatal.[22] Heat stress in the hot workplace can also affect cognitive performance, metabolism, body temperature, heart rate, and blood pressure, resulting in various disorders and diseases. It can also impact working memory, storage, and information processing and increase the likelihood of errors and accidents.[20]

Heat stroke is a dangerous condition that can occur when the core temperature reaches 40°C or higher. It causes an immediate inflammatory response and changes the way that white blood cells stick to the walls of blood vessels. Studies have shown that heat stroke temperatures cause endothelial cells to become overactive, leading to an excessive buildup of white blood cells in the microcirculation, which can damage tissues.[20]

Muscle or heat cramps commonly happen when there is prolonged exposure to excessive heat and when the individual's fitness level and ability to tolerate heat are low, but their training intensity is high. The loss of sodium due to heavy sweating is believed to be a crucial factor in causing muscle or heat cramps, which results in the contraction of the interstitial fluid compartment and over-stimulation of the neuromuscular junction. On the other hand, some research indicates that abnormal control of motor neurons in the spinal cord causes neuromuscular fatigue, leading to muscle cramps during exercise. The exact mechanisms that lead to heat cramps are still debatable, but it is probably due to a mix of sodium depletion, dehydration, and/or neuromuscular fatigue.[1]

According to research, the use of thermal protective barriers in military, occupational, and athletic settings can lead to decreased performance and cause cardiovascular and thermal strain. When soldiers and first responders wear protective clothing in hot environments, they experience an elevated heart rate and rectal temperature, which can lead to fatigue and a decrease in endurance. Studies have shown that these physiological changes can cause exhaustion in a shorter amount of time compared to when wearing lighter non-protective clothing.[23]

The impact of heat stress is not limited to physiological changes and can also affect an individual's perceptions [thermal sensation, perception, or comfort; wetness; breathing comfort; rating of perceived exertion (RPE); and cognitive function]. Researchers have conducted studies on thermal perceptions during hot weather. The outcomes of these studies indicate acceptable limits for human exposure to hot temperatures.[23, 24]

Thermal sensation and thermal comfort are distinct concepts in that thermal sensation is linked to skin temperature, whereas thermal comfort depends on the overall condition of the body's thermoregulatory system.[25] Thermal sensation is a cognitive perception that can be described as hot or cold and is primarily based on input from thermal receptors in the skin. On the other hand, thermal comfort is an affective experience that can be described as comfortable or uncomfortable, pleasant, or unpleasant.

Heat sensation is calculated as a function of the local T_{sk} and T_{co}. Quinn et al[26]., have demonstrated that wearing a personal cooling device (PCD) in combination with impermeable personal protective equipment (PPE) can effectively reduce the increases in T_{co}, Ts, heat sensation, and weight loss. The specific characteristics of the PCD can impact the degree of improvement in these variables. In occupational settings with high heat stress, the use of a PCD under impermeable PPE may be a useful strategy to decrease the risk of heat-related injuries. While thermal manikin modeling can provide a reliable estimation of T_{co} and heat sensation, T_{sk} may be overestimated, and weight loss may be underestimated.[26]

To determine the best way to manage the adverse effects of heat stress on physiological and cognitive function, researchers have conducted multiple studies, including those by Hemmatjo et al[27]., Ciuha et al[28]., and Barr et al.[18] A recent study found that continuous cooling approaches are effective in managing heart rate elevation and temperature fluctuations, indicating their usefulness in controlling physiological effects associated with heat stress. These studies also found that continuous cooling can improve cognitive function, as indicated by improved response accuracy. However, the effectiveness of different continuous cooling approaches varies.[27]

Cooling Strategies

There are different types of cooling vests that can be classified based on the cooling mechanism they use. These include ice cooling vests, air-cooled vests (ACVs), liquid-cooled vests

(LCVs), evaporative cooling vests (ECVs), phase change cooling vests (PCVs), and hybrid cooling vests (HCVs).

During the early stages of the development of Personal Cooling Garments, ice cooling garments were commonly used due to their simplicity and affordability. These garments had specific pockets designed to hold ice which would absorb the heat generated from the skin, resulting in a drop in temperature and increased thermal comfort in hot weather.[29] They were widely used in industries such as protective garments, athletic wear, and military uniforms due to their low cost and high availability. Studies by Juhani et al.[30] and Cooter et al.[31] showed that the ice cooling vest effectively cooled the skin temperature and improved work efficiency and endurance performance during sustained heavy work. However, prolonged contact with ice can cause tissue irritation and the heavy weight, large volume, and cooling interruption have limited the use of ice cooling garments in daily life. To address these issues, gel ice cooling technology has been explored as a promising alternative. Studies by Dehghan et al.[9] and Chesterton et al.[32] have shown that ice gel cooling vests can effectively reduce skin temperature and heat strain score index during light activities but may not be as effective as frozen peas in skin freezing and calming.

Air-cooled vests (ACVs) operate by continuously supplying either ambient or compressed air into the vest microenvironment.[33] This promotes the evaporation of sweat and convection, which helps to dissipate heat. The effectiveness of ACVs is influenced by skin moisture and the vapor pressure of the ambient air. ACVs restrict movement if they are connected to a fixed source of air, but if they have a battery-powered fan, then there are no such restrictions. These vests can provide either cooled or ambient air, but the latter is not very effective in hot and humid conditions or while wearing personal protective clothing because of restricted convective and evaporative heat loss.

Liquid-cooled vests (LCVs) work by circulating cooled liquid, usually water, through small tubes that are embedded in the inner layer of the vest, close to the skin.[8] The liquid is pumped from a bladder or a container that can be stored in the back pocket of the vest (if it is portable) or in a separate unit/container (if it is stationary).

Evaporative cooling vests (ECVs) work by wetting the surface of the vest, which helps to increase the amount of evaporation from the vest or clothing surface.[34] This evaporation leads to an increase in the temperature gradient between the skin surface and the surface of the vest, which enhances heat loss from the skin.

Phase change cooling vests (PCVs) use inserts that are filled with a material, such as a gel, that changes from a solid to a liquid state when it absorbs heat, and from a liquid to a solid state when it releases heat.[35] This mechanism allows the vest to extract heat from the body mainly through conduction. PCVs are especially useful in hot and humid environments and when worn under protective clothing where evaporative and convective heat loss is not possible or restricted.

Hybrid cooling vests combine two or more of the cooling concepts described above. Phase change and evaporative cooling vests have a limited operational duration compared to ACVs connected to a fixed air source and LCVs, which offer continuous and uninterrupted cooling. However, ACVs and LCVs require auxiliary equipment and a constant power source for their operation. On the other hand, mobile ACVs and LCVs are powered by rechargeable batteries, so their operational time is limited by the battery's capacity. Therefore, PCVs and ECVs are considered passive cooling garments, while ACVs and LCVs are considered active cooling garments.

Comparing Cooling Strategies in Various Studies

Barr et al[18]. determined that wearing ice vests during a 15-minute recovery period, which primarily relies on conductive pathways to release heat, does not offer any extra advantages compared to hand and forearm immersion alone. Ice vests also do not impact core body temperature when used separately during operations in which firefighters have to return to work following short rest periods.

Kajiki and colleagues[36] evidenced that a backpack that is equipped with battery-powered fans and allows air to pass through it can effectively reduce the rise in body temperature, heart rate, and physiological strain index, as well as enhance ratings of perceived exertion, thermal sensation, and overall comfort during 60 minutes of walking in a hot environment (35°C, 50% RH). This air- perfused backpack can decrease both physical and perceptual stress experienced during light physical activity in hot conditions. Therefore, this device could be beneficial in mitigating heat stress among workers and audience members at the Tokyo Olympics and Paralympics. However, the individuals in the study wore the cooling vests without any protective garments, and simply wore a t-shirt.

Hematjo and colleagues[27] found that cooling vests coated with phase change material are more effective in reducing physiological responses and cognitive function impairment during firefighting and life-saving operations than cooling garments containing menthol. In addition, using a cooling vest in conjunction with a cooling garment does not provide any extra benefit. Therefore, it can be concluded that cooling the body with a cooling vest is beneficial for the physiological and cognitive functions of firefighters during simulated firefighting activities.

The use of vests containing frozen PCM and gel inserts offers intense but brief cooling, while evaporative vests provide a gentler cooling effect over a longer period. As a result, the former may not be suitable for workers who require an 8-hour shift. Once the cooling capacity of the vest is depleted, it can hinder the body's natural thermoregulation. In such situations, vests that provide moderate to mild cooling over a longer duration would be preferred. However, different environmental conditions can lead to different results. Sweating is a crucial method for dissipating heat, with a liter of sweat removing around 2400 kJ of heat energy. In high humidity environments, sweat evaporation is compromised, which makes PCM or gel insert vests more suitable.[8]

Yuan and colleagues[10] conducted research to examine the impact of a personal cooling vest on the physiological and perceptual strain experienced by individuals wearing stab-resistant body armor in a hot environment. The use of the liquid cooling vest (LCV) resulted in a reduction in mean skin temperature, scapula skin temperature, and evaporation efficiency, and helped to mitigate the increase in thermal sensation. Furthermore, the LCV had a minimal effect on core temperature, heart rate, oxygen consumption, sweat loss, RPE, and restriction of movement. In essence, the LCV had a limited ability to reduce physiological strain, such as core temperature and heart rate, but did provide a thermal sensation to the user. Their study provides useful information for the development of personal cooling systems, evaluation of heat stress, and determination of the maximum working duration in hot environments.

The LCV vests were effective in significantly reducing torso T_{sk} (to the lowest measured level between 29 and 30 °C) during the first half of the 2.5-hour walk. However, their cooling ability[23] declined thereafter, and by the end of the walk, they had reached similar levels as the control trial. The researchers noted some performance differences between the various stages of the trial, including improved reaction times after the walk-in comparison to baseline scores. When participants wore the LCV vests, their torso T_{sk} eventually rose to a similar level as the control group by the end of the walk, causing discomfort and heat. Additionally, during the trials with the LCV vest, there was an improvement in the memory test. The plausible explanation for this outcome could be found in change of mental alertness. The possible reasons for this are that an increase in thermal perception and a decrease in thermal comfort may have caused activation of the sympathetic nervous system, resulting in increased mental awareness. This was demonstrated by an improvement in memory test scores.[28]

Hashimoto and colleagues[24] found that the cooling vest used circulating water maintained at a temperature of 10.0 °C. After two exercise sessions of 30 minutes each, the rectal temperature (Tre) was 0.3 °C lower under the VEST condition than under the CON condition. When the garment was worn in an environment with a temperature of 40 °C and relative humidity (RH) of 50%, heat dissipation through evaporation was greater than heat convection from the hot ambient air.

Contrast to the expectations, the Tre was consistently higher in the VEST condition than in the CON condition during the first exercise session. This could be because the vest interfered with the evaporation of sweat from the upper and middle trunk, while the core body heat gradually dissipated to the skin surface. Additionally, the cold water circulating throughout the vest may have constricted the arteriovenous anastomosis in the subcutaneous region, inhibiting heat dissipation from the skin surface through heat conduction and convection.[37]

Kim et.al[11] suggested that simulated firefighting, in combination with wearing protective clothing and exposure to high temperatures, is a physically demanding activity that can cause significant physiological and thermal strain. Using passive recovery, which relies on natural body cooling through evaporation for a short period of time before engaging in strenuous physical activity again, was found to be an ineffective cooling strategy for reducing thermal strain or restoring the body to its baseline state. This was particularly true in hot and humid conditions.

Therefore, they researched two types of LCGs and found that wearing a shortened whole body cooling garment (covered head, torso, forearm, and thigh) underneath the firefighting gear was found to significantly reduce thermal strain, improve recovery, and extend the length of subsequent exercise bouts. However, they discovered that the top cooling garment (covered head and forearm), could not alleviate heat strain during a short recover phase and enhance a subsequent task performance.[11]

Aljaroudi[6] et al. discovered that wearing a liquid cooling garment underneath firefighting personal protective equipment significantly reduced physiology and thermal strain but did not have any clear benefit on attention and inhibition due to the limitations of cooling method used in their study. Nonetheless, they suggest adding cooling equipment to firefighters' gear can help mitigate industrial hyperthermia, maintain their reaction times, and prevent unsafe decision- making, ultimately improving their performance and productivity.

Some studies mentioned above focused on the cooling benefits of LCG for individuals who engage in continuous, moderate-intensity physical activity for a sustained period. However, certain professions, such as firefighting, involve short periods of strenuous work followed by brief periods of rest, typically lasting less than one hour. This type of activity differs from the continuous moderate-intensity physical activity studied in previous research.[25]

The National Fire Protection Association recommends that firefighters stop working after 30 to 60 minutes, depending on the duration of their self-contained breathing apparatus, the level of exertion, and the environment. After stopping work, they should rest for 10 to 20 minutes before resuming firefighting. However, it has been shown that simply cooling the body passively, such as through sweating or removing protective gear, is not an effective way to reduce body heat and prevent overheating. Previous studies have investigated active cooling methods for firefighters, including using vests with ice packs or phase changing materials, cooling fans, and cold-water immersion, during both work and rest periods.

Liquid cooling garments (LCG) were originally used in aviation and space missions and have been found to be a safe, effective, and strong cooling method for preventing heat stress and promoting thermal comfort during physical activity and exposure to external heat. Several studies have also investigated the effectiveness of using LCG under protective clothing, such as nuclear, biological, and chemical (NBC) clothing, and military protective clothing. These studies have shown that using LCG significantly reduces the level of thermal strain and heat storage, while also improving work performance and increasing tolerance to heat stress during prolonged physical activity.

The objective of this research was to compare the efficacy of the same cooling power applied to either upper body or whole body cooling systems in reducing physiological and thermoregulatory stress, improving subjective responses, and enhancing cognitive function during exercise in a hot environment while wearing firefighter turnout gear. It was hypothesized that cooling will be beneficial with whole body cooling being more effective than upper body cooling.

CHAPTER 3: MANUSCRIPT

ABSTRACT

Introduction: Firefighters operating in hot environments face challenges from protective garments that restrict heat dissipation, resulting in increased core temperature, thermal discomfort, and performance decline. Cooling vests represent a viable solution. The study aim was to compare effectiveness of the same amount of cooling power to the upper body (UB) or whole body (WB) in alleviating thermoregulatory and physiological stress, enhancing cognitive function, and reducing ratings of thermal discomfort and exertion, during 60 min of exercise in a hot environment (40°C, 40% relative humidity) while wearing firefighter turnout gear. **Methods**: Eight healthy individuals (27.5±3 y) participated in three conditions with either no cooling (Control) or active cooling with a liquid perfused shirt (UB cooling), or with a liquid perfused shirt and pants (WB cooling). In each trial, participants performed three sets of 15 min of stepping (20 steps/min) and 5 min of rest. **Results**: Both cooling strategies were beneficial compared to having no cooling at all. Participants could only complete two exercise bouts during Control, but they completed all three bouts with active cooling. WB cooling provided an advantage over UB cooling for core and skin temperature, and thermal comfort and sensation. The advantage in minimizing the increase in core temperature was only evident during the third exercise bout. **Conclusion**: Active cooling is advantageous under these conditions. WB cooling provided some benefits versus UB cooling during heavy intensity exercise; however, it is uncertain whether these benefits would be observed during light-to-moderate exercise, which more likely reflects an actual firefighting scenario.

Key Words/phrases: heat illness, firefighter gear, cooling garments, thermoregulation, hot environment exercise.

INTRODUCTION

Significant heat stress is a common risk in various commercial, industrial, and emergency response operations.[1] Excessive body heating is a risk from high ambient temperature and/or humidity, and excessive workloads. These factors are exacerbated in some occupations by protective clothing, such as body armor, nuclear biological chemical suits, or firefighter turn out gear. For example, military, law enforcement and firefighter personnel (e.g., airports or rocket launch sites) wear these garments during their missions to enhance their safety. However, these garments can hinder the body's ability to dissipate heat because they limit heat loss to the environment due to high insulation and low permeability to water vapor which reduces the thermoregulatory function of sweating. Diminished heat loss can lead to an increase in core temperature (T_{co}) which can cause heat illness, reduce work output, impair cognitive function and decision making, produce erratic behavior, and increase the likelihood of accidents. Previous research has addressed prevention of body core heating during exercise in the heat while wearing protective clothing.[2, 6]

[7]A liquid cooling garment (LCG) is a popular form of cooling technology. It operates by using a liquid coolant, such as water or ethylene glycol, as the circulating fluid. The coolant is stored in a reservoir and circulated through a network of tubing inside the garment using external power, such as a battery-powered micropump. There are several studies on the effectiveness of liquid cooling vests, and some have reported them as effective for reducing physiologic load,[6, 28] but not cognitive inhibition and attention.[6] These studies primarily examined vests that cover only the torso. Little work has been done on the effect of cooling more than the upper body.

One study found that a specialized LCG covering the head, torso, thighs, and lower arms was effective in decreasing the physiological and thermal heat strain compared to a LCG that covered only the head and lower arms, or no cooling at all.[11] These results are not surprising because the specialized LCG had not only an increased surface area but also a threefold increase in flow rate. It is not known which body surface configuration would be more effective if the cooling power (e.g., the total liquid flow rate) is the same. Interestingly, head, and lower arm cooling did not improve core temperature or exercise time compared to no cooling.

Koscheyev[12] cooled different body segments with 8°C water and demonstrated that cooling capacity for the upper body including torso, upper arms, and forearms (5.18 kcal/min), was higher than for the lower body including the thigh and calves (3.71 kcal/min) in resting participants. Therefore, it might seem best to apply all cooling power to the upper body. However, if leg exercise is involved, heat production of, and blood flow to, the lower body will be proportionally greater, and redistributing some cooling to the lower body may be beneficial. Also, concentrating all cooling to a smaller total surface area (e.g., the upper body) may result in excessive cold discomfort.

The purpose of this study was to compare the efficacy of the same cooling power applied to either upper body or whole body cooling systems in reducing physiological and thermoregulatory stress, improving subjective responses, and enhancing cognitive function during exercise in a hot environment while wearing firefighter turnout gear. It was hypothesized that cooling would be beneficial and that whole body cooling would be more effective than upper body cooling.

METHODS

Participants

The experimental protocol was approved by the University of Manitoba Research Ethics Board 1 (HE2023-0101). This study was registered in ClinicalTrials.gov (NCT05890261). Eight participants (two women) were (mean±SD) 27.5±3 y old, 175.6±8 cm tall, with body mass of 73.6±12 kg, and 13.8±5% body fat (measured by bioelectrical impedance analysis, InBody USA, Cerritos, CA). On three occasions they wore firefighter 'turnout gear' in a protocol including three 15-min exercise bouts [step test in 40°C air and 40% relative humidity] each followed by a 5-min rest period.

Materials

Core temperature (°C) was monitored with an ingestible pill (e-Celsius, Hérouville Saint Clair, France) that continuously monitored, recorded, and wirelessly transmitted core temperature. Skin temperature (T_{skin}, ºC) was measured with small metal discs (iButton, Whitewater, USA) taped to the skin at the following six sites on the left side of the body: chest, abdomen, upper arm, lower arm, anterior thigh, and anterior calf.[2, 38, 39] Heart rate (HR) was measured with a smart garment (tank top shirt, Hexoskin Wearable Body Metrics, Montreal) worn directly against the skin in all conditions. Oxygen consumption (V_{O2}) was continuously monitored with a metabolic cart (Parvo Medics, Utah, USA).

Sweat loss was calculated as follows. Upon arriving at the lab, participants were weighed in the clothing that they wore to the lab (this was considered their "reference clothing"). They then changed into their exercise clothing (under shorts, sport shorts, Hexoskin shirt, and bra if necessary). Following the exercise protocol, they removed their exercise clothing and dried their skin off. They then put on their "reference clothing" and were weighed a final time. Total sweat loss mass was calculated as follows: m_{sweat} loss = ($m_{body+reference\ clothing\ i}$) - ($m_{body+reference\ clothing\ f}$), where m_{sweat} loss is the mass of sweat lost during the entire protocol, $m_{body+reference\ clothing}$ is the mass of the participant plus the dry reference clothing worn to the lab, and $_i$ and $_f$ refer to initial and final measurements respectively.[2]

To ensure proper hydration status prior to each trial, urine specific gravity (USG) was determined. Participants provided a urine sample, and a reagent strip was used to determine the USG (Multistix 10 SG, Bayer). To be eligible to start a trial, a USG value equal to or below 1.020 was required, indicating minimal dehydration.[2] If the initial USG reading was 1.021 or higher, participants were instructed to consume 2-3 cups of water, and a second test was conducted approximately 1 hour later. If necessary, this process was repeated until the USG met the inclusion criteria.

Participants rated their perceived exertion (RPE) on a scale ranging from 6 (no exertion at all) to 20 (maximal exertion).[40] They then rated their thermal sensation on a scale ranging from -3 (cold) to +3 (hot),[41] and their thermal discomfort on a scale of 0 (comfortable) to 4 (extremely uncomfortable).[26] They then rated their breathing discomfort on a scale of 1 (no discomfort) to 7 (intolerable discomfort).[5] Skin wetness was rated using a scale of 1 (dry) to 5 (soaked).[5]

Cognitive function was assessed with the mini-cog test which is a brief screening tool.[42] This test involved two components: a three-item recall test and a clock-drawing task. First, participants were asked to repeat three unrelated words that were spoken by the tester. They then were asked to draw a clock face including all the numbers (1 to 12), with the hands correctly showing a specific time that was given to them. Then they were asked to repeat the original three words in the correct order. The recall test is scored out of three points (one point for each word correctly recalled in the proper order), while the clock-drawing task is scored out of two points (one point for the correct placement of the numbers and one point for the correct time). The scores from the two components were added together. A score of 0-2 suggests cognitive impairment, while a score of 3-5 suggests normal cognitive function.

Participants participated in three trials, each involving three 15-min exercise bouts followed by 5 min of rest with either no cooling or one of two different cooling conditions using liquid cooling garments (e.g., long sleeved shirt and full length pants; Allen-Vanguard, ON, Canada). Each cooling garment was inlayed with tubing at 10-15 mm intervals. The conditions were defined as follows: Control (C) with no cooling garments; Upper body cooling (UB) with the cooling shirt (weight, 0.4 kg) worn over the Hexoskin shirt and beneath the firefighter turnout gear; and Whole-body cooling (WB) with both cooling shirt and pants (total weight, 0.8 kg) worn over the Hexoskin shirt and sport shorts, and beneath the turnout gear. The Hexoskin shirt covered ~70% of the surface area of the cooling shirt and the sport shorts covered ~50% of the surface area of the cooling pants. The order of conditions was randomly assigned to achieve a balanced design. Each subject chose a paper from a box that included all different conditions.

The cooling garments were perfused with 2°C water at a flow rate of 1.8 L/min from just prior to entering the chamber until the end of the recovery period. Thermocouples measured inflow and outflow water temperatures from either the shirt (e.g., UB condition) or the combined shirt and pants (e.g., WB condition). Values were recorded every 5 min while in the chamber. The turnout gear consisted of jacket, pants, and helmet weighing a total of 6.5 kg. Participants wore their own footwear, and they did not carry self-contained breathing apparatus.

Procedure

Each participant performed their trials at the same time of the day to control for circadian effects (heart rate, body temperature and hormone level). They were asked to refrain from smoking, consuming alcohol, and performing moderate-to-heavy exercise within 24 h before each trial. They were also asked to drink 2–3 glasses of water and eat a moderately sized meal no less than 1 h prior to arrival.

On arrival at the laboratory a urine sample was collected for the analysis of USG. After instrumentation, participants sat in the laboratory [ambient temperature (T_{air}) ~20°C] for 15 min of baseline measurements (**Fig. 2**). Participants then entered a chamber (T_{air} of 39±1°C and 41±4% relative humidity) where they performed a 60-min exercise and rest routine. This included three sets of 15 min of stepping exercise at a rate of 20 steps per min (step height 22.5 cm high), followed by a 5-min seated rest period during which the subjective and cognitive measures were taken. After completing the exercise and rest protocols, participants then exited the chamber and sat for an additional 15 min. The entire clothing ensembles were worn throughout each 90-min protocol. The exercise test was terminated, and the participant exited the chamber if: the core temperature reached 39°C; the participant felt light-headed or nauseous; the participant indicated a wish to stop; or a researcher felt the participant should stop for any reason.

Subjective and cognitive assessments were taken at the following times (**Fig. 1**): 15 min prior to exercise (baseline), during the three rest periods in the chamber, and 10 min after exiting the chamber. After each participant completed their three trials, they were asked to comment on which cooling condition they preferred and why?

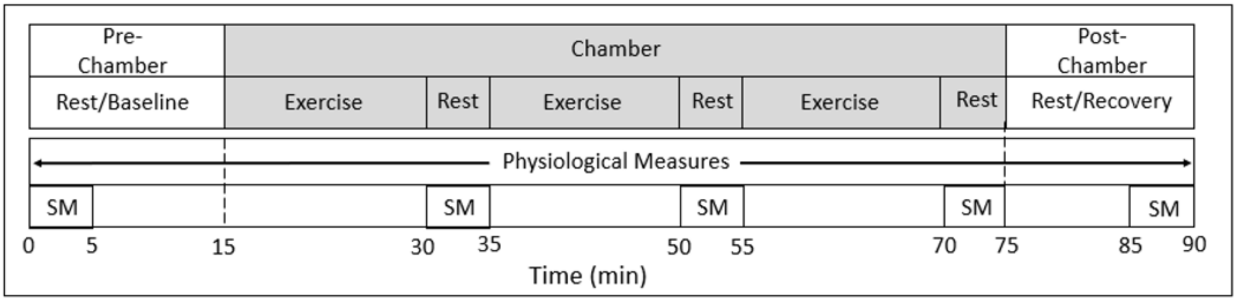

Figure. 2. Test protocol. Subjects sat in the laboratory for 15 min of rest/baseline (pre-chamber), then entered a heat chamber (Tair, 39±1°C and 41±4% RH) for 60 min. They performed three sets of 15 min of stepping exercise, followed by 5 min of rest. Subjects then exited the chamber (post-chamber) for 15 min of rest/recovery. Physiological variables were measured continuously, and subjective and cognitive measurements (SM) were made during rest periods.

Data Analysis

The head, feet and hands were not included in this analysis, therefore the regional area percentages for the six measured sites totaled 84% (e.g., chest, 18%; abdomen, 18%; upper arm, 9%; lower arm, 6%; anterior thigh, 18%; and anterior calf, 15%). These percentages were used to calculate area-weighted T_{skin} for the total body (all six sites), upper body (UB, four sites), and lower body (LB, two sites) according to previous work in our lab.[2]

Heat production was calculated as follows:

$$\text{Heat production (kcal/min)} = VO_2\ (\text{L } O_2/\text{min}) \cdot 4.825\ \text{kcal/L } O_2,$$

where a respiratory quotient of 0.82 for a mixed diet was assumed.

Heat removal in each cooling condition was calculated as follows:

$$Q\ (W) = m_w \cdot c_w \cdot (T_{out} - T_{in}) \cdot 69.7,$$

where Q = heat flow (positive values indicate loss from body); m_w = water flow rate (L/min); c_w = specific heat of water (1 kcal/kg · °C); T_{out} and T_{in} = outlet and inlet water temperature respectively (°C); and 69.7 is the conversion factor (e.g., 69.7 W/kcal/min).

All statistical analyses were performed with the SigmaStat package within the SigmaPlot 14 (Systat Software, San Jose, California, USA). Group results were reported as mean±SD. All data were subjected to a Shapiro-Wilk test for normality. Physiologic measurements were continuously measured throughout each trial. Two-way analysis of variance (ANOVA) for repeated measures (for factors time and cooling condition) was used to compare data from baseline, the end of each exercise and rest period, and the end of the recovery period. A one-way ANOVA was used to compare total sweat loss for the three conditions. Tukey's test was used for *post hoc* analysis of significant differences. Subjective and cognitive measures were analyzed with two-way nonparametric Friedman's ANOVA on Ranks Test if the normality test (Shapiro-Wilk) failed, while the two-way ANOVA was used if the normality test passed. When data were only available for two conditions (e.g., UB and WB at 70 min), a Wilcoxon Signed Rank Sum Test was used. A paired t-test compared mean heat removal between the two cooling conditions. Statistical significance was set at P=0.05 for all tests.

RESULTS

Urine specific gravity was equal to or below 1.020 for all trials. All eight participants completed all three exercise bouts in UB and WB conditions, but none were able to start the third exercise bout in the Control condition. Six managed to complete the second bout while two (one male and one female) stopped 11 and 11.5 min into the second bout. Seven participants terminated exercise because T_{co} reached 39°C and the other one felt dizzy and could not continue. In the

Control condition all participants rested for 5 min in the heat and then exited the chamber to rest another 15 min in the laboratory. Because no participants were able to start a third exercise bout in the Control condition, two separate analyses were conducted. The first two-way ANOVA included all three conditions from 0-45 min and a second two-way ANOVA included just two conditions (e.g., UB and WB) from 50-90 min.

At the end of baseline, there were no inter-condition differences in T_{co} (**Fig. 3**). During the initial exercise bout, T_{co} rose similarly from baseline (~0.6°C) in all three conditions (F=102, DF=4, P<0.001). Core warming was arrested during the first rest period. In the second exercise bout, at 45 min, the last point during which all participants were still exercising, T_{co} increased significantly in Control (P<0.001) and UB cooling (P=0.009) but not WB cooling. At this point, T_{co} was 0.5°C higher in Control compared to both cooling conditions (F=49.8, DF=2, P<0.001). Then, during the third exercise bout, T_{co} significantly increased in the UB condition (0.5°C; F=22.8, DF=4, P<0.001) but not the WB condition. During the third rest period, T_{co} decreased 0.5°C in the UB (P=0.002) and 0.3°C in the WB condition (P=0.05). During the 15-min recovery period outside the chamber, T_{co} remained elevated during Control, decreased significantly in the UB condition (P<0.001) and did not change in the WB condition. At the end of recovery, T_{co} was 1.7°C higher in Control than the two cooling conditions (F=49.8, DF=2, P<0.001).

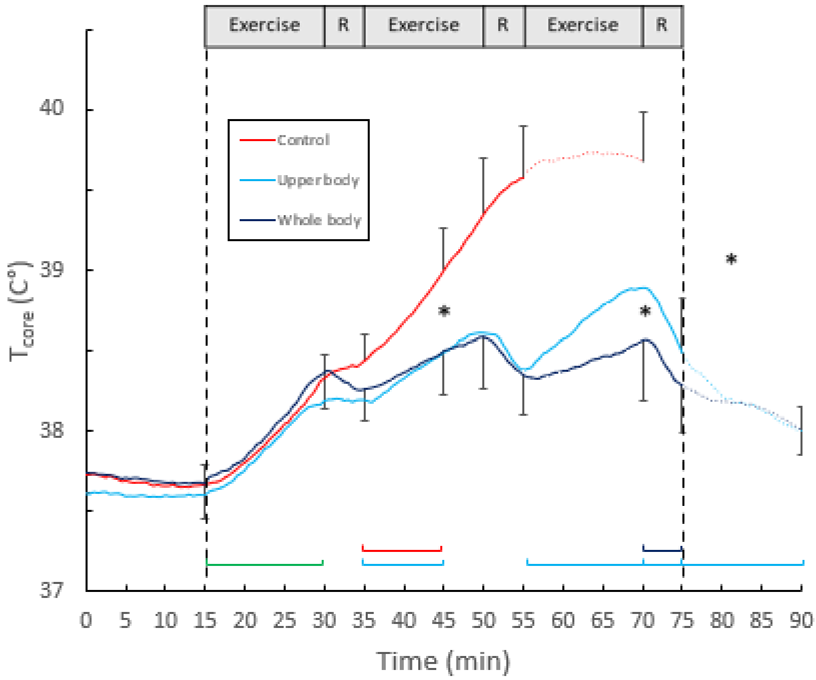

Figure. 3. Mean core temperature (Tcore, °C) for three conditions (n=8). Dotted lines show the recovery time outside the chamber (this occurred after the second exercise bout of Control). SD bars are only presented above or below lines for clarity. R, rest period; Exercise, stepping exercise at a rate of 20 steps per min. * Significant difference between conditions (p<0.05). Horizontal brackets indicate differences within each condition (red, Control; light blue, Upper body cooling; dark blue, whole body cooling; green, all conditions) (P<0.05).

Baseline $T_{skin\ total}$ was similar for all three conditions (**Fig. 4, top**). During the first exercise bout, $T_{skin\ total}$ rose 2°C in the Control condition (F=98.4, DF=4, *P*<0.001) and decreased 2°C with UB and 7°C with WB cooling (*P*<0.001). Values were different between all three conditions (F=200.9, DF=2, *P*<0.001). Values did not change throughout the remainder of exercise and rest periods for any condition. During the 15-min recovery period outside the chamber, values remained elevated during Control, but decreased during UB and WB cooling (F=66.7, DF=4, *P*<0.001).

Baseline $T_{skin\ UB}$ was similar for all three conditions (**Fig. 4, middle**). In Control, temperature rose 2°C during the first exercise bout (F=102.8, DF=4, *P*<0.001) and remained elevated throughout the remainder of exercise and rest periods. In the cooling conditions, temperature decreased 6°C during the first exercise bout ($P<0.001$) and remained at these levels throughout the remainder of exercise and rest periods. At the end of the 15-min recovery periods outside the chamber, temperature decreased ~3°C in both cooling conditions ($F=41.9$, $DF=4$, $P<0.001$) and these values were ~14°C below the Control condition ($F=261.7$, $DF=2$, $P<0.001$).

Baseline $T_{skin\ LB}$ was similar for all three conditions (**Fig. 4 bottom**). In Control and UB cooling conditions, temperature rose 2.5-3.0°C during the first exercise bout ($F=39.3$, $DF=4$, $P<0.001$) and remained elevated throughout the remainder of exercise and rest periods. During WB cooling, temperature decreased 7°C during the first exercise bout ($P<0.001$) and remained at these levels throughout the remainder of exercise and rest periods. At the end of the 15-min recovery periods outside the chamber, temperature decreased 2°C with UB cooling and 4°C with WB cooling ($F=75.4$, $DF=4$, $P<0.001$) with values being 1 and 1°C lower than Control respectively ($F=156.6$, $DF=2$, $P<0.001$).

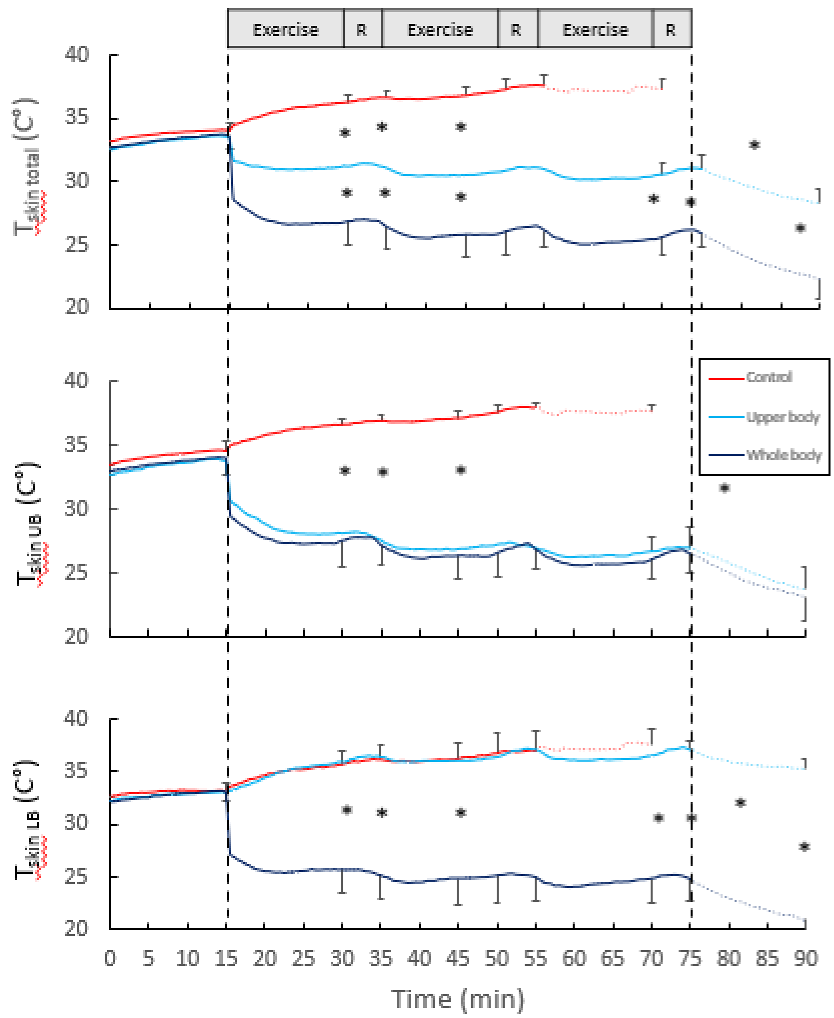

Figure. 4. Mean skin temperature (°C) for three conditions (n=8). (Top) Skin temperature of total body (Tskin total); (Middle), skin temperature of upper body (Tskin UB); and (Bottom) skin temperature of lower body (Tskin LB). Dotted lines show the recovery time outside the chamber. SD bars are only presented above or below lines for clarity. * Significant difference between conditions (p<0.05).

There were no significant differences in HR between conditions during baseline (**Fig. 5, top**). Following the initial exercise bout HR increased form baseline by 63 to 87 b/min across all three conditions (F=308.7, DF=4, P<0.001) with values being higher in Control compared to both cooling conditions (F=12.1, DF=2, *P*<0.001). After the initial rest period, HR significantly decreased by about 55 b/min across all three conditions but remained higher in the Control condition (*P*<0.001).

During the second exercise bout, at 45 min, the last point during which all participants were still exercising, HR significantly increased by 62 b/min in the Control condition (F=308.7, DF=4, *P*<0.001) and by 64 b/min in the cooling conditions (*P*<0.001). At this point, HR was higher in Control compared to both cooling conditions (F=12.1, DF=2, *P*<0.001).

During the third exercise bout, in the cooling conditions HR increased significantly (F=552.6, DF=4, *P*<0.001), then during the third rest period, significantly decreased (*P*<0.001) to values that were similar to the start of that bout. During the 15-min recovery period outside the chamber, HR decreased significantly in all conditions (*P*≤0.002). At the end of recovery, HR was about 40 b/min higher in Control than both cooling conditions (F=12.1, DF=2, *P*<0.001).

Baseline heat production was similar for all three conditions (**Fig. 5, bottom**). In the first two exercise bouts, heat production increased significantly (F=283.9, DF=4, *P*<0.001) and similarly in all three conditions, and returned to near baseline values during rest periods. In the third exercise bout and rest period, heat production increased (F=165.1, DF=4, *P*<0.001) and decreased similarly in the two cooling conditions.

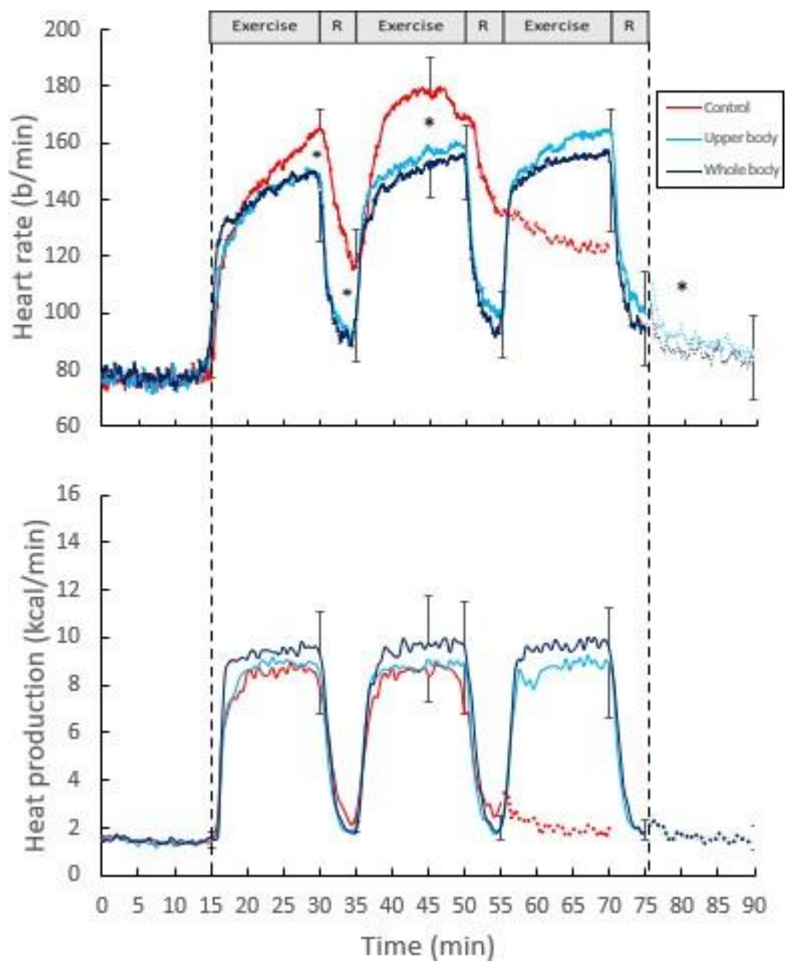

Figure. 5.top; (Top) Mean heart rate (b/min), and (Bottom) heat production (kcal/min) for three conditions (n=8). Dotted line shows the recovery time outside the chamber. SD bars are only presented above or below lines for clarity. R, rest period; Exercise, stepping exercise at a rate of 20 steps per min. * Significant difference between conditions (p<0.05).

Total sweat loss during Control (1,175±504 ml) was significantly greater than with WB cooling (512±242 ml; F=13.6, DF=2, *P*<0.001) but not UB cooling (838±169 ml; *P*=0.056); values were not significantly different between WB and UB.

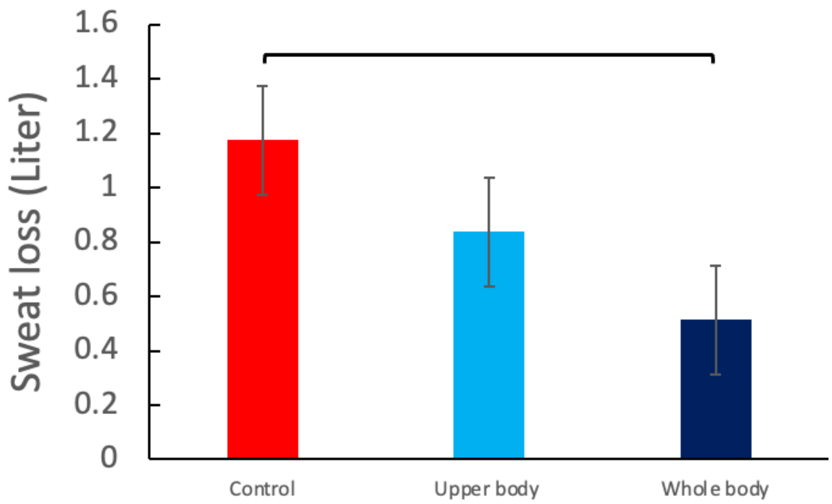

Figure.6 Sweat loss in Control condition only for 2 exercise bouts while included three exercise bout for cooling conditions. Black horizontal bracket indicates differences between conditions (P<0.05).

After the first exercise bout RPE was similar for all three conditions (**Fig. 7, top**). At the end of the second exercise bout, RPE increased during both the Control condition (F=18.6, DF=1, *P*<0.001) and the UB cooling condition (*P*=0.025), with the Control values being higher than both cooling conditions (F=9.4, DF=2, *P*≤0.005). There was no difference in RPE between cooling conditions at the end of the third exercise bout.

Breathing discomfort was low (e.g., ~1.5, no discomfort to very mild discomfort) and similar in all conditions during baseline (**Fig. 7, bottom**). In the Control condition, breathing discomfort increased after the first exercise bout (value ~3, mild discomfort; F=25.2, DF=3, *P*=0.001) and increased further at the end of the second exercise bout (value ~5, severe discomfort; *P*<0.001).

Discomfort did not increase with either cooling condition and values were lower than Control after both the first (F=22.5, DF=2, *P*=0.027) and second (*P*<0.001) exercise bouts.

Breathing discomfort did not increase in cooling conditions during the third exercise bout. At the end of the recovery period outside the chamber breathing discomfort decreased in all three conditions (e.g., ~2, very mild discomfort; F=25.2, DF=3, *P*≤0.03) and values were higher in the Control than both cooling conditions (F=22.5, DF=2, *P*<0.001).

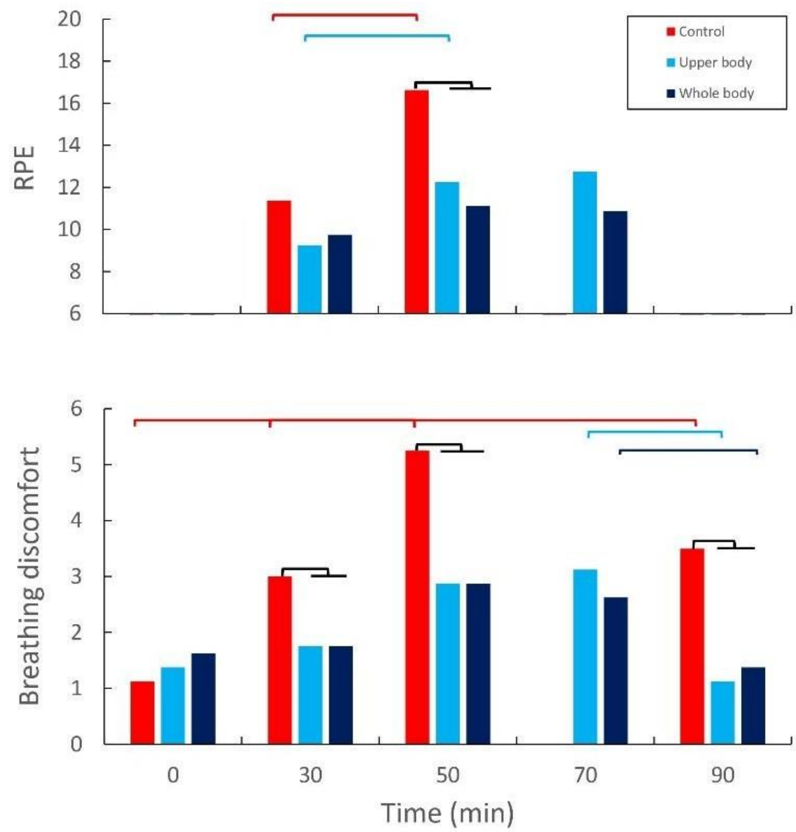

Figure. 7 (Top) Mean RPE for three conditions on a scale ranging from 6 (no exertion at all) to 20 (maximal exertion), during rest periods following each of three exercise bouts in the chamber (n=8). (Bottom) Mean breathing discomfort on a scale of 1 (no discomfort) to 7 (intolerable discomfort), during pre-chamber rest, three rest periods in the chamber, and post-chamber recovery (n=8). Colored horizontal brackets indicate differences within each condition (red, Control; light blue, Upper body cooling; dark blue, whole body cooling) (P<0.05). Black horizontal brackets indicate differences between conditions (P<0.05).

Thermal sensation was low (e.g., <1, neutral to slightly warm) and similar in all conditions during baseline (**Fig. 8, top**). In the Control and UB conditions, sensation increased after the first exercise bout (F=61.6, DF=3, *P*<0.001 and P=0.008 respectively) and remained elevated after the second exercise bout. Thermal sensation did not significantly increase during WB cooling. Values were different between all three conditions at the end of the first and second exercise bouts ($F=65.8$, $DF=2$, $P\leq0.012$). After the third exercise bout sensation remained higher with UB cooling than WB cooling ($F=13.9$, $DF=1$, $P=0.02$). After 15 min of recovery outside the chamber, sensation decreased in all three conditions ($F=61.6$, $DF=3$, $P<0.001$), with the Control condition values being higher than both cooling conditions ($F=65.8$, $DF=2$, $P<0.001$).

Thermal discomfort was low (e.g., ~0, comfortable) and similar in all conditions during baseline (**Fig.8, middle**). Discomfort did not increase in either cooling condition in the first or second exercise bouts. However, in the Control condition, discomfort increased from baseline to the second exercise bout (e.g., 4, extremely uncomfortable; $P<0.001$) and at this point was greater than the WB cooling ($P=0.045$). Thermal discomfort did not increase in either cooling condition during the third exercise bout and at this point the value was higher with UB cooling than WB cooling ($F=1.5$, $DF=1$, $P=0.042$). Then, after 15 min of recovery outside the chamber, discomfort with UB cooling decreased (e.g., ~0, comfortable; $P<0.001$) and at this point UB cooling had lower values compared to the Control condition ($P=0.045$).

Skin wetness was low (e.g., ~1.5, dry to somewhat dry) and similar in all conditions during baseline (**Figure 8 bottom**). During the first exercise bout, wetness increased similarly and significantly with Control and UB cooling ($F=58.2$, $DF=3$, $P<0.001$) but not with WB cooling. During the second exercise bout, skin wetness did not increase in any condition, but at this point, Control values were greater than both cooling conditions ($F=23.1$, $DF=2$, $P\leq0.0.13$). During the third exercise bout, values did not change in either cooling condition. At the end of the 15-min recovery period outside the chamber, skin wetness had not decreased in any condition. At this point, wetness was higher in Control than with WB cooling (*P*<0.001) but not UB cooling.

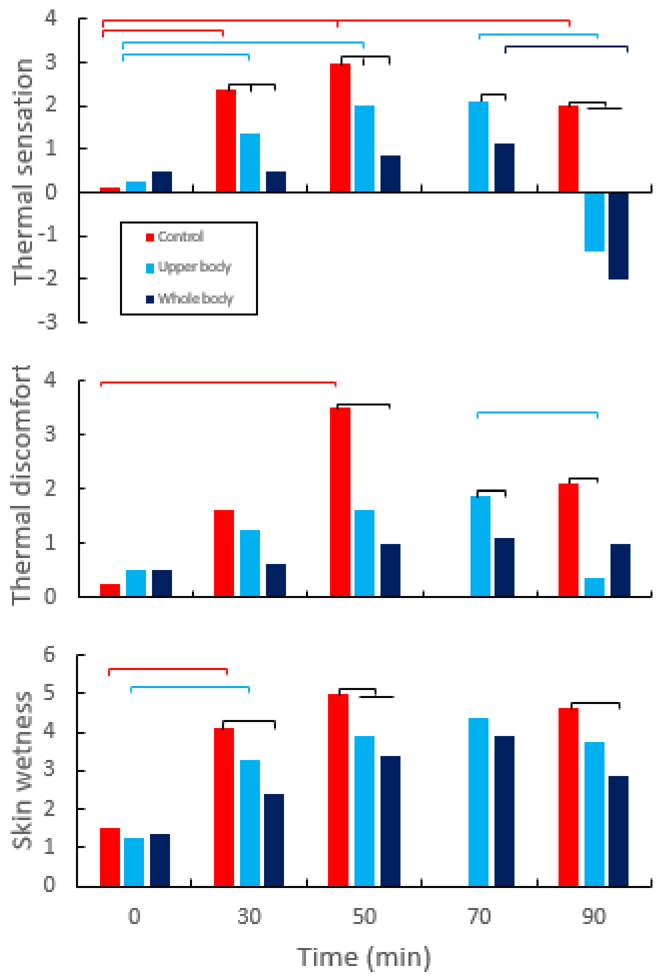

Figure. 8 (Top) Median thermal sensation for three conditions on a scale ranging from -3 (cold) to +3 (hot) (n=8). (Middle) Mean thermal discomfort on a scale of 0 (comfortable) to 4 (extremely uncomfortable) (n=8). (Bottom) Mean skin wetness on a scale of 1 (dry) to 5 (soaked) (n=8). Values are for three conditions during pre-chamber rest, three rest periods in the chamber, and post-chamber recovery. Colored horizontal brackets indicate differences within each condition (red, Control; light blue, Upper body cooling; dark blue, whole body cooling) ($P<0.05$). Black horizontal brackets indicate differences between conditions ($P<0.05$).

Throughout the entire duration of the protocol, there were no significant differences in cognitive function across all three conditions (*P*=0.179).

Four of eight participants preferred the WB cooling conditions because their legs felt too warm during UB cooling. Of the other four participants, three preferred the UB condition because they felt too cold during WB cooling, and one felt that the pants created too much restriction to motion during WB cooling.

During the 60-min period in the chamber, heat removal for each cooling condition was consistent except for a brief decrease during rest periods. Average heat removal with WB cooling (785±68 W) was greater than with UB cooling (667±95 W; t=3.8, DF=7, *P*=0.007).

DISCUSSION

To our knowledge, this is the first study to compare the effectiveness of applying the same cooling power to either the upper body or the whole body in mitigating physiological and thermal stress, enhancing subjective responses, and improving cognitive function during exercise in a hot environment while wearing firefighter turnout gear.

Our hypothesis, that cooling would be beneficial compared to Control was supported for all variables except cognition, which did not change throughout trials in any condition. Our secondary hypothesis that it would be better to apply the same amount of cooling power to the whole body compared to the upper body was supported for core and skin temperature, and thermal sensation and comfort. However, the benefits of the two cooling conditions over Control were similar for heart rate, RPE, breathing discomfort and perception of skin wetness.

The benefits shown in this study of liquid cooling garments in attenuating the increase in T_{co} are consistent with previous studies during heavy exercise in the heat[6, 11] and light-to-moderate exercise in the heat.[24, 28] The lower T_{co} with WB cooling than UB cooling in the third exercise bout is also consistent with results from Kim et al.[11] who demonstrated lower T_{co} with a liquid cooling garment that covered a greater surface area. However, this garment (covering head, arms, torso, and thighs) also had a three times higher flow rate than the garment with lesser surface area (covering only head and forearms), while we used the same flow rate for both UB and WB conditions.

Our results demonstrating that cooling attenuates the increased heart rate during exercise in the heat, are consistent with studies using a liquid cooling garment covering either the upper body only[28] or whole body.[6] Our results are also consistent with those of Kim et al.[11] who demonstrated that cooling the upper body or whole body (with increased water flow rate) decreased heart rate compared to Control but were not different from each other. Our results showing no affect on cognitive function were also consistent with those of Aljaroudi et al.[6] This would indicate that the heat and exercise load were not enough in either study to invoke a cognitive decrease as measured by the mini-cog test.

A previous study on exercise in the heat demonstrated that a liquid cooling vest does not affect sweat rate during low intensity exercise for 2.5 h.[28] However, with moderate intensity exercise for 60 min, cooling resulted in a tendency for sweat to decrease (e.g., from 1,090 to 800 ml) although this difference was not significant.[17] The present study with heavy exercise during 60 min of heat exposure demonstrated a significant decrease from 1,175 ml sweat during Control to 512 ml sweat with WB cooling. Sweat loss during UB cooling (838 ml) was not quite significantly lower than Control (P=0.056), however it should be noted that sweat loss for Control was only for 2 exercise bouts (e.g., 40 min of exercise in the heat chamber). If participants could have completed a third exercise bout during Control, total sweat loss would have been higher, and the difference would likely be significant. Perception of skin wetness throughout the trials, was qualitatively similar to total sweat loss.

Previous studies support our subjective results which demonstrated that cooling conditions improved thermal discomfort[24] and sensation, and reduced RPE.[24] We are unaware of any similar studies addressing breathing discomfort. Ciuha et al.[28] did not see an improvement in RPE with cooling and only saw an improvement in thermal sensation for the first half of their 2.5 h protocol. This difference demonstrates the limitations of their vest which used a 2 L reservoir filled with ice and a battery powered pump. Although the pump functioned for the entire trials, the cooling power decreased during the second half of the trials as the ice had melted at this point, thus T_{sk} which had cooled by ~5°C in the first half, returned to baseline levels by the end of the trials. This contrasts with the present study in which an essentially infinite heat sink resulted in a continued decrease in T_{sk} through the trials. *In toto*, these results indicate that with light-to-moderate exercise, cooling does not affect physiological measures during shorter exercise protocols (e.g., 50-60 min)[22] but attenuates the increase in T_{co} and heart rate during longer exercise protocols (e.g., 2.5 h).[28] However, during heavy exercise in the heat, as in the study by Hashimoto et al.[24] and the present study, cooling improves all measured physiological variables and improves RPE and other subjective measures.

Even though heat production, and therefore oxygen consumption, was similar for all three conditions, heart rate was higher in the cooling conditions than Control. Since the work rate was similar for all conditions, blood flow to exercising muscles would also be similar. However, the warmer Control condition would cause an increase in thermoregulatory skin blood flow, in order to dissipate heat. Cardiac output would thus be higher, which is consistent with the increased heart rate in this condition.

Compared to UB cooling, WB body cooling decreased skin temperature by ~5°C and increased heat removal by ~18%, however a difference in core temperature was not evident until the third exercise bout. Thermal sensation and comfort followed changes in skin temperature.

The level and type of exercise in this study did not accurately represent tasks performed during actual firefighting. A high work rate was used to increase the possibility to demonstrate differences between cooling conditions, and step exercise was easily reproducible. Greater external validity might be attained with more realistic firefighting activities such as sled drag, ladder extension, hose roll raise and kit carry.

It was not possible to determine total heat balance because heat flux was not measured. Finally, the phase of the menstrual cycle was not controlled for the two female participants and future studies should control for this as the hormonal fluctuations during menstruation is crucial for understanding how they may affect physical performance, including body temperature regulation.

These results demonstrate that either cooling strategy is beneficial compared to having no cooling at all. During heavy exercise, WB cooling provided an advantage for core and skin temperature, and thermal comfort and sensation. Importantly, the advantage in minimizing the increase in core temperature was only evident during the third exercise bout.

It is uncertain whether the same benefits would be observed during light-to-moderate exercise, which is likely more common during an actual firefighting scenario. At these reduced work rates, it is possible that the advantages of WB cooling may become apparent only after a longer duration of activity. Given these results and the increased cost and technical difficulty associated with also cooling the lower body, it would be preferable to develop a practical, portable system for upper body cooling.

Future studies should include longer duration trials with lower exercise intensities to determine if WB cooling provides any advantage over UB cooling at these levels. If an advantage of WB cooling is demonstrated, a subsequent study could incorporate tasks that are more relevant to firefighting scenarios.

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We thank the participants who contributed their time to this study. Without their cooperation, this research would not have been possible.

CHAPTER 4: SUMMARY

This study discusses the risks of heat stress in various occupations, particularly those requiring protective clothing, and the limitations of such garments in dissipating heat, leading to increased core temperature and various health issues. The focus was on cooling systems, liquid cooling garment, as a solution. Previous studies have mainly examined the effectiveness of LCG covering only the torso.

Heat stress during physical activity, particularly in hot environments, is explored. Sweating is a key mechanism, but excessive heat accumulation can lead to uncompensable heat stress, negatively affecting cardiovascular, muscular, and cognitive functions. This study noted the importance of maintaining heat balance, discusses the impact of heat stress on performance.

Various cooling strategies, including ice vests, air-cooled vests, liquid-cooled vests, evaporative cooling vests, phase change cooling vests, and hybrid cooling vests, are detailed. Studies comparing these strategies are summarized, revealing differences in effectiveness based on factors like cooling duration and environmental conditions.

The aim of this research was to compare the efficacy of the same cooling power applied to either upper body or whole body cooling systems in reducing physiological and thermoregulatory stress, improving subjective responses, and enhancing cognitive function during exercise in a hot environment while wearing firefighter turnout gear. It was hypothesized that cooling will be beneficial with whole body cooling being more effective than upper body cooling.

In this study, eight subjects (27.5±3 y) participated in three trials involving 15-minute exercise bouts in firefighter 'turnout gear' in a 40°C environment with 40% humidity.

Physiological measurements, including core and skin temperature, heart rate, oxygen consumption, and sweat loss, were recorded. Subjects were hydrated adequately, and subjective assessments such as rate of perceived exertion, thermal sensation, thermal discomfort, breathing discomfort, and skin wetness were obtained. Cognitive function was assessed using the mini-cog test. The trials included three cooling conditions: Control (no cooling garments), Upper body cooling (cooling shirt), and whole body cooling (cooling shirt and pants). Cooling garments were perfused with 2°C water during the cooling trials. The study followed a specific protocol, and data analysis involved various calculations, including heat production and removal. Statistical analyses were conducted using ANOVA and nonparametric tests (Friedman's ANOVA on Ranks Test), with significance set at $P \leq 0.05$.

All subjects completed the exercise bouts in UB and WB conditions, but none could start the third bout in the Control condition. Core temperature increased similarly during the initial exercise in all conditions. During the second exercise bout, T_{co} increased significantly in Control and UB cooling but not WB cooling. At the end of the second bout, T_{co} was lower in cooling conditions compared to Control. In the third bout, T_{co} increased in UB but not WB, and during recovery, T_{co} decreased in both cooling conditions but remained elevated in Control.

$T_{skin\ total}$ increased in Control condition, while it decreased with cooling conditions. $T_{skin\ UB.}$ increased in Control, while it decreased with cooling with lower values in WB cooling. $T_{skin\ LB}$ increased in Control and UB while it decreased in WB cooling. Heart rate increased in all conditions during exercise, with higher values in Control. Heat production increased similarly in all conditions during exercise bouts. Total sweat loss was greater in Control than WB but not significantly different from UB. Rating of Perceived Exertion increased more in Control than cooling conditions after the second exercise bout. Breathing discomfort increased in Control but not in cooling conditions. Thermal sensation and discomfort increased in Control and UB but not WB. Skin wetness increased similarly in Control and UB during the first exercise bout. Cognitive function showed no significant differences across conditions. Then, four subjects preferred WB cooling, while three preferred UB due to feeling too cold during WB cooling, and one cited motion restriction during WB cooling. Heat removal was greater with WB cooling compared to UB.

In conclusion, to our knowledge both cooling approaches are advantageous over doing none at all. WB cooling offered benefits for skin and core temperatures, as well as thermal comfort and sensation, during intense exercise. Crucially, the benefit of reducing the rise in body temperature was only noticeable in the third exercise session.

Limitations of the study include the use of a high work rate that may not accurately represent actual firefighting tasks. Overall, the results suggest that both cooling strategies are beneficial, with WB cooling providing advantages in minimizing core temperature increase during heavy exercise. Further research is needed to assess the applicability of these findings to firefighting scenarios with different exercise intensities and durations.

REFERENCES

(1) Périard, J. D.,Eijsvogels, T. M. H.,Daanen, H. A. M. Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. Physiol Rev 2021, 101 (4), 1873-1979. DOI: 10.1152/physrev.00038.2020.

(2) Giesbrecht, G. G.,Jamieson, C.,Cahill, F. Cooling hyperthermic firefighters by immersing forearms and hands in 10 degrees C and 20 degrees C water. Aviat Space Environ Med 2007, 78 (6), 561-567.

(3) Goforth, C.,Lisman, P.,Deuster, P. The physiological impact of body armor cooling devices in hot environments: a systematic review. Mil Med 2014, 179 (7), 724-734. DOI: 10.7205/milmed-d-13-00398.

(4) Zare, M.,Dehghan, H.,Yazdanirad, S.,Khoshakhlagh, A. H. Comparison of the impact of an optimized Ice cooling vest and a paraffin cooling vest on physiological and perceptual strain. Saf Health Work 2019, 10 (2), 219-223. DOI: 10.1016/j.shaw.2019.01.004.

(5) Quinn, T.,Kim, J. H.,Strauch, A.,Wu, T.,Powell, J.,Roberge, R.,Shaffer, R.,Coca, A. Physiological evaluation of cooling cevices in conjunction with personal protective ensembles recommended for use in West Africa. Disaster Med Public Health Prep 2017, 11 (5), 573-579. DOI: 10.1017/dmp.2016.209.

(6) Aljaroudi, A. M.,Kadis, D. S.,Bhattacharya, A.,Strauch, A.,Quinn, T. D.,Williams, W. J. Effect of continuous cooling on inhibition and attention while wearing firefighter's PPE in a hot environment. J Occup Environ Hyg 2020, 17 (5), 243-252. DOI: 10.1080/15459624.2020.1726933.

(7) Bartkowiak, G.,Dabrowska, A.,Marszalek, A. Assessment of an active liquid cooling garment intended for use in a hot environment. Appl Ergon 2017, 58, 182-189. DOI: 10.1016/j.apergo.2016.06.009.

(8) Ciuha, U.,Valenčič, T.,Mekjavic, I. B. Cooling efficiency of vests with different cooling concepts over 8-hour trials. Ergonomics 2021, 64 (5), 625-639. DOI: 10.1080/00140139.2020.1853820.

(9) Ren, S.,Han, M.,Fang, J. Personal Cooling Garments: A Review. Polymers (Basel) 2022, 14 (24). DOI: 10.3390/polym14245522 From NLM.

(10) Yuan, M.,Wei, Y.,An, Q.,Yang, J. Effects of a liquid cooling vest on physiological and perceptual responses while wearing stab-resistant body armor in a hot environment. International Journal of Occupational Safety and Ergonomics 2022, 28 (2), 1025-1032. DOI: 10.1080/10803548.2020.1858618.

(11) Kim, J. H.,Coca, A.,Williams, W. J.,Roberge, R. J. Effects of liquid cooling garments on recovery and performance time in individuals performing strenuous work wearing a firefighter ensemble. J Occup Environ Hyg 2011, 8 (7), 409-416. DOI: 10.1080/15459624.2011.584840.

(12) Koscheyev, V. S.,Coca, A.,Leon, G. R.,Dancisak, M. J. Individual thermal profiles as a basis for comfort improvement in space and other environments. Aviat Space Environ Med 2002, 73 (12), 1195-1202.

(13) Lim, C. L.,Byrne, C.,Lee, J. K. Human thermoregulation and measurement of body temperature in exercise and clinical settings. Ann Acad Med Singap 2008, 37 (4), 347-353.

(14) Bligh, J. A theoretical consideration of the means whereby the mammalian core temperature is defended at a null zone. J Appl Physiol (1985) 2006, 100 (4), 1332-1337. DOI: 10.1152/japplphysiol.01068.2005 From NLM.

(15) Hurrie, D. M. G.,Talebian Nia, M.,Power, K.,Stecina, K.,Gardiner, P.,Lockyer, E.,Giesbrecht, G. G. Spinal and corticospinal excitability in response to reductions in skin and core temperatures via whole-body cooling. Appl Physiol Nutr Metab 2022, 47 (2), 195-205. DOI: 10.1139/apnm-2021-0370.

(16) Webb, P. The physiology of heat regulation. Am J Physiol 1995, 268 (4 Pt 2), R838-850. DOI: 10.1152/ajpregu.1995.268.4.R838 From NLM.

(17) Romanovsky, A. A. The thermoregulation system and how it works. Handb Clin Neurol 2018, 156, 3-43. DOI: 10.1016/b978-0-444-63912-7.00001-1.

(18) Barr, D.,Reilly, T.,Gregson, W. The impact of different cooling modalities on the physiological responses in firefighters during strenuous work performed in high environmental temperatures. Eur J Appl Physiol 2011, 111 (6), 959-967. DOI: 10.1007/s00421-010-1714-1.

(19) Cheung, S. S.,McLellan, T. M.,Tenaglia, S. The thermophysiology of uncompensable heat stress. Sports Medicine 2000, 29 (5), 329-359. DOI: 10.2165/00007256-200029050-00004.

(20) Rastegar, Z.,Ghotbi Ravandi, M. R.,Zare, S.,Khanjani, N.,Esmaeili, R. Evaluating the effect of heat stress on cognitive performance of petrochemical workers: A field study. Heliyon 2022, 8 (1), e08698. DOI: 10.1016/j.heliyon.2021.e08698.

(21) Périard, J. D.,Racinais, S.,Sawka, M. N. Adaptations and mechanisms of human heat acclimation: Applications for competitive athletes and sports. Scand J Med Sci Sports 2015, 25 Suppl 1, 20-38. DOI: 10.1111/sms.12408 From NLM.

(22) Nori-Sarma, A.,Sun, S.,Sun, Y.,Spangler, K. R.,Oblath, R.,Galea, S.,Gradus, J. L.,Wellenius, G. A. Association between ambient heat and risk of emergency department visits for mental health

among US adults, 2010 to 2019. JAMA Psychiatry 2022, 79 (4), 341-349. DOI: 10.1001/jamapsychiatry.2021.4369 (acccessed 2/25/2023).

(23) Pryor RR, C. D., Adams WM, Belval LN, DeMartini JK, Huggins RA, Stearns RL, ,LW, V. Maximizing Athletic Performance in the Heat. Strength and Conditioning Journal 2013, 24-33.

(24) Hashimoto, K.,Horie, S.,Nagano, C.,Hibino, H.,Mori, K.,Fukuzawa, K.,Nakayama, M.,Tanaka, H.,Inoue, J. A fan-attached jacket worn in an environment exceeding body temperature suppresses an increase in core temperature. Sci Rep 2021, 11 (1), 21269. DOI: 10.1038/s41598-021-00655-2.

(25) Pantavou, K.,Theoharatos, G.,Mavrakis, A.,Santamouris, M. Evaluating thermal comfort conditions and health responses during an extremely hot summer in Athens. Building and Environment 2011, 46 (2), 339-344. DOI: https://doi.org/10.1016/j.buildenv.2010.07.026.

(26) Quinn, T.,Kim, J. H.,Seo, Y.,Coca, A. Comparison of thermal manikin modeling and human subjects' response during use ofcooling devices under personalprotective ensembles in the heat. Prehosp Disaster Med 2018, 33 (3), 279-287. DOI: 10.1017/s1049023x18000328.

(27) Hemmatjo, R.,Motamedzade, M.,Aliabadi, M.,Kalatpour, O.,Farhadian, M. The effect of practical cooling strategies on physiological response and cognitive function during simulated firefighting tasks. Health Promot Perspect 2017, 7 (2), 66-73. DOI: 10.15171/hpp.2017.13.

(28) Ciuha, U.,Valenčič, T.,Ioannou, L. G.,Mekjavic, I. B. Efficacy of cooling vests based on different heat-extraction concepts: The HEAT-SHIELD project. J Therm Biol 2023, 112, 103442. DOI: 10.1016/j.jtherbio.2022.103442.

(29) Muir, I. H.,Bishop, P. A.,Ray, P. Effects of a novel ice-cooling technique on work in protective clothing at 28 degrees C, 23 degrees C, and 18 degrees C WBGTs. Am Ind Hyg Assoc J 1999, 60 (1), 96-104. DOI: 10.1080/00028899908984427.

(30) Smolander, J.,Kuklane, K.,Gavhed, D.,Nilsson, H.,Holmér, I. Effectiveness of a light-weight ice-vest for body cooling while wearing fire fighter's protective clothing in the heat. Int J Occup Saf Ergon 2004, 10 (2), 111-117. DOI: 10.1080/10803548.2004.11076599 From NLM.

(31) Cotter, J. D.,Sleivert, G. G.,Roberts, W. S.,Febbraio, M. A. Effect of pre-cooling, with and without thigh cooling, on strain and endurance exercise performance in the heat. Comp Biochem Physiol A Mol Integr Physiol 2001, 128 (4), 667-677. DOI: 10.1016/s1095-6433(01)00273-2 From NLM.

(32) Chesterton, L. S.,Foster, N. E.,Ross, L. Skin temperature response to cryotherapy. Arch Phys Med Rehabil 2002, 83 (4), 543-549. DOI: 10.1053/apmr.2002.30926 From NLM.

(33) Kuklane, K.,Lundgren, K.,Gao, C.,Löndahl, J.,Hornyanszky, E. D.,Östergren, P.-O.,Becker, P.,Samuels, M. C.,Gooch, P.,Sternudd, C.; et al. Ebola: improving the design of protective clothing for emergency workersa allows them to better cope with heat stress and help to contain the epidemic. The Annals of Occupational Hygiene 2015, 59 (2), 258-261. DOI: 10.1093/annhyg/mev003 (acccessed 3/22/2023).

(34) Havenith, G.,Bröde, P.,den Hartog, E.,Kuklane, K.,Holmer, I.,Rossi, R. M.,Richards, M.,Farnworth, B.,Wang, X. Evaporative cooling: effective latent heat of evaporation in relation to evaporation distance from the skin. J Appl Physiol (1985) 2013, 114 (6), 778-785. DOI: 10.1152/japplphysiol.01271.2012.

(35) Maley, M. J.,Minett, G. M.,Bach, A. J. E.,Stewart, K. L.,Stewart, I. B. Extending work tolerance time in the heat in protective ensembles with pre- and per-cooling methods. Applied Ergonomics 2020, 85, 103064. DOI: https://doi.org/10.1016/j.apergo.2020.103064.

(36) Kajiki, M.,Yamashita, N.,Ito, R.,Matsumoto, T. Effects of air-perfused rucksack on physiological and perceptual strain during low-intensity exercise in a hot environment. Temperature (Austin) 2020, 7 (2), 157-164. DOI: 10.1080/23328940.2020.1757991.

(37) Meng, X.,Xue, S.,An, K.,Cao, Y. Physiological indices and subjective rhermal perception of heat stress-exposed workers in an industrial plant. Sustainability 2022, 14 (9), 5019.

(38) Layton R, M. W., Annis J, et al. Calorimetry with heat flux transducers: comparison with a suit calorimeter. J Appl Physiol (1985) 1983, 54:1361–1367.

(39) DuBois D, D. E. A formula to estimate the approximate surface area if height and weight are known. Arch Intern Med 1916, 17:863–871.

(40) Borg, G. A. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982, 14 (5), 377-381.

(41) Rincón, J.,Bojorquez, G.,Calderon, C.,Fuentes Freixanet, V. Thermal comfort indoors: a factor that influences the environmental perception of the occupants (case study: student community of the autonomous University of Baja California). Modern Journal of Language Teaching Methods 2017. DOI: DOI: 10.26655/mjltm.2017.8.1.

(42) Brown, M. T.,Brangman, S. A.,Smith, N. H. Early identification of cognitive impairment: utility of the Mini-Cog in non-clinical settings. J Appl Gerontol 2023, 42 (10), 2139-2147. DOI: 10.1177/07334648231175606.

APPENDIX

Thermal comfort

Determine the level of comfort experience:

(0)-comfortable
(1)-slightly comfortable (2)-uncomfortable
(3) -very uncomfortable (4)-extremely uncomfortable

Thermal sensation

How hot or cold you feel?

(+3)- Hot
(+2)- Warm
(+1)- Slightly warm (0)- Neutral
(-1)- Slightly cool (-2)- Cool
(-3)- Cold

Raring of perceived exertion

Evaluate the intensity of exercise:

6:
7: Very, very light
8:
9: Very light
10:
11: Fairly light
12:
13: Somewhat hard
14:
15:
16:
17: Very hard
18:
19:
20: Very, very hard

Breathing comfort

How would you rate your level of discomfort in relation to your breathing?

1 = no discomfort
2 = very mild discomfort
3 = mild discomfort
4 = moderate discomfort
5 = severe discomfort
6 = very severe discomfort
7 = intolerable discomfort

Subjective wetness

How wet do you feel?

1 -Dry
2 -Somewhat dry
3 -Neither dry nor wet 4 - Somewhat wet
5 -Soaked

T_{skin} Calculations

$T_{skin\ total}= (T_{CH}.18/84) + (T_{AB}.18/84) + (T_{TH}.18/84) + (T_{calf}.15/84) +(T_{UA}.9/84) + (T_{LA}.6/84)$

$T_{skin\ UB}= (T_{CH}.18/84) + (T_{AB}.18/84) + (T_{LA}.18/84) + (T_{UA}.9/84)$

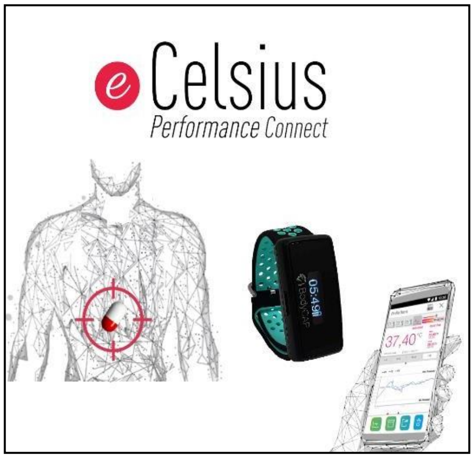
$T_{skin\ LB}= (T_{TH}.18/84) + (T_{calf}.15/84)$

CH: Chest, AB: Abdomen, TH: Thigh, LA: Lower arm, UA: Upper arm

$T_{skin\ total}$ included all six sites: chest, abdomen, upper arm, lower arm, anterior thigh, and calf.

$T_{skin\ UB}$ included four sites: chest, abdomen, upper arm, lower arm.

$T_{skin\ LB}$ included two sites: anterior thigh, and calf.



eCelsius pills for T_{co}

iButton for Tskin

Hexoskin shirt to measure HR and respiration

Hexoskin shirt Liquid-perfused garments Firefighter turnout gear