ABSTRACT

MICA, MUSHFIKA TASNIM. The Effect of Wearing Ballistic Vests on Firefighter Heat Strain. (Under the direction of Drs. Emiel DenHartog and Roger Barker).

Firefighters and emergency medical technicians are increasingly exposed to hostile, non-fire emergency scenarios that involve ballistic threats, yet their protective equipment has traditionally been designed around a single-disciplined fire paradigm. Although ballistic vests offer critical protection against firearm-related injuries, their integration with multilayer firefighting turnout gear introduces additional thermal burden that may significantly elevate heat strain and compromise operational performance. Despite growing adoption of ballistic protection by fire departments, limited quantitative data exist to guide equipment selection, design optimization, and standards development with respect to combined ballistic and thermal performance. This research provides a systematic, quantitative evaluation of the thermal and physiological consequences of wearing ballistic vests in conjunction with firefighter turnout gear. Six ensemble configurations, incorporating multiple ballistic vest combinations with station uniform and turnout suits, were evaluated using standardized thermal manikin testing to quantify whole-ensemble and regional thermal resistance (R_t), evaporative resistance (R_{et}), and total heat loss (THL). These experimentally derived clothing parameters were then integrated into validated thermophysiological modeling to predict core temperature, mean skin temperature, and cardiovascular strain.

Results demonstrated that the addition of ballistic vests significantly increases torso-level thermal and evaporative resistance, producing a marked reduction in total heat loss while wearing them with a station uniform. However, although the addition of a turnout suit on top of the station uniform increases R_t and R_{et} significantly, the addition of ballistic vests with the turnout suit does not increase the thermal properties significantly. Also, the positioning of

ballistic vests, whether they are placed on top of the turnout jacket with or without hard plates or underneath the jacket, does not change the R_t or R_{et} values significantly compared to the turnout suit alone. However, while comparing the male R_t and R_{et}, the findings demonstrated that anatomical differences in torso shape, particularly chest curvature, torso circumference, and breadth, directly affect how garments and ballistic vests fit and consequently how air layers are formed or compressed. Gender-specific analyses highlighted the limitations of male-based design paradigms and provided evidence-based direction for advancing gender-responsive firefighter PPE.

When sweating manikin data were incorporated into human thermal modeling, the physiological implications of these material and anatomical differences became evident. The findings indicated that metabolic scaling under equivalent METs, rather than clothing design alone, governed much of the observed gender-related thermal response. The data also demonstrated that although females face a modest disadvantage in lighter clothing, males accumulate disproportionately greater heat strain under humid and multilayered conditions, highlighting the combined effects of anatomy, clothing compression, and environmental vapor pressure on gender-specific thermal burden. Analyses of extreme body sizes further demonstrate that anthropometric variability strongly influences core temperature responses under identical environmental and clothing conditions. Collectively, these results highlight the limitations of average-body or gender-only models and underscore the need to incorporate body-size and percentile-based considerations into thermophysiological modeling, work-rest guidance, and protective ensemble evaluation

By combining standardized manikin testing with physiologically validated modeling, this study introduces a framework for assessing the thermal cost of ballistic protection in firefighter ensembles. The outcomes generate new, actionable knowledge for firefighters, equipment manufacturers, and standards organizations, supporting informed PPE selection, design innovation, and the development of performance criteria that balance ballistic protection with thermal safety and firefighter wellness.

The Effect of Wearing Ballistic Vests on Firefighter Heat Strain

by
Mushfika Tasnim Mica

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APPROVED BY:

Dr. Emiel DenHartog (Co-chair)

Dr. Roger Barker (Co-chair)

Dr. Kavita Mathur

Dr. Jeff Joines

Dr. Jason Painter

DEDICATION

I dedicate this dissertation to my parents, whose love and encouragement have sustained me throughout this journey. I am especially grateful to them for instilling in me the values of perseverance and curiosity. To my daughter, Nayirah Mehvish Hossain, who has given me new purpose and hope for the future. And to my cat Luke, a loyal companion whose quiet presence brought comfort and peace in long days and nights of work.

BIOGRAPHY

Mushfika Tasnim Mica was born and raised in Pabna, Bangladesh. She completed her undergraduate degree in Textile Engineering at Bangladesh University of Textiles. She then traveled halfway across the world to pursue a Master of Science in Apparel Design at the University of Wyoming, where she learned that designing apparel involves creativity, technical precision, and convincing sewing machines to cooperate. This experience allowed her to bridge engineering logic with design thinking and sparked a deeper interest in the science behind clothing performance. It inspired her to pursue her PhD in Textile Technology Management at North Carolina State University and joined Textile Protection and Comfort Center in 2022 under the supervision of Dr. Roger Barker.

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AUTHORSHIP STATEMENT

Contribution of Mushfika Tasnim Mica and coauthors are listed below for each chapter

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1. Mushfika Tasnim Mica: sole author of Chapter 1.

Chapter 2

1. Mushfika Tasnim Mica: sole author of Chapter 2.

Chapter 3

1. Mushfika Tasnim Mica: Writing including abstract, introduction, conducting interviews, data analysis of both survey and interview, discussion and conclusion.
2. Marc Mathews: Survey design and conducting the survey.
3. Roger Barker: contributed to the acknowledgement and shaping the discussion portion.
4. Anthoney Deaton: Edits and feedback.
5. Emiel DenHartog: Edits and feedback.

Chapter 4

1. Mushfika Tasnim Mica: sole author of Chapter 4.

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1. Mushfika Tasnim Mica: sole author of Chapter 5.

Chapter 6

1. Mushfika Tasnim Mica: sole author of Chapter 6.

Generative Artificial Intelligence tools were used in a limited capacity during the preparation of this dissertation to help with language refinement, including correcting grammar, and thereby improving overall readability of the text. All substantive content, including the research questions, research design, data collection, analysis, interpretation of results, and conclusions, was developed independently by the author. Therefore, the author takes full responsibility for the accuracy, originality, and integrity of the work presented.

CHAPTER 1

INTRODUCTION

Firefighting is a highly physically demanding job where personnel must engage in various tasks with minimal limitations on their movements. The increased risk of terrorist attacks in the United States has emphasized the need to enhance the safety of first responders, specifically firefighters, from chemical, biological, and radiological dangers without adding to their physical strain [1]. Over the last decades, there has been a significant shift in the types of emergencies firefighters respond to. Traditionally, fighting fire has long been considered a primary duty of firefighters. Nowadays, the local fire department is typically dispatched in an emergency to rescue individuals in danger. The majority of these incidents don't include a fire. According to the government report on emergency responses in the USA, only approximately 4% of emergency calls to fire departments in 2020 were related to fire. 64% of the reported calls to fire departments were associated with a wider range of non-fire scenarios, including mass shootings, medical emergencies, hazardous materials, search and rescue operations, and civil unrest [2] [3]. Thus, present firefighters might be considered "all-hazards responders," in charge of handling all emergencies and disasters. As a consequence, the number of firefighters who died from activities at non-fire scenes has increased [4].

Police officers and firefighters are frequently required to work together, but their lack of specialized training and equipment prevents them from entering each other's high-risk sectors [5]. The capacity of police personnel to respond to hostile occurrences can be hindered by visibility problems caused by fire and heat injury. On the other hand, firefighters are not equally prepared for situations involving fire and weapons. As a result, executing combined operations when multiple threats are present is extremely dangerous for firefighters without any additional protection. Tragic deaths from firearms injuries leave little doubt that firefighters need ballistic protection in some emergency response scenarios. Howard M. Munding, a former fire inspector of the Peoria (AZ) Fire Department, indicated that an estimated 700,000 attacks against firefighters and emergency medical technicians (EMTs) take place each year [6]. Between 2019 and 2024, 122 incidents occurred in the USA where firefighters were shot and killed while responding to non-fire scenarios [7]. Therefore, firefighters need to be appropriately equipped with ballistic gear when accomplishing cross-disciplined combined missions that challenge traditional, single-disciplined response paradigms. Ballistic vest use, however, may cause thermal discomfort [8]. Thus, adding ballistic vests to firefighters' gear could make these issues more complicated. Research studies have tested the thermal strain of ballistic vests for law enforcement officers and the thermal strain of firefighters while wearing turnout gear. However, there have been limited or no studies where the thermal strain was tested for firefighters wearing ballistic vests with turnout gear.

Reports of bullet injuries to firemen and emergency medical technicians (EMTs) are often found in media reports and firefighter periodicals. However, no scientifically based research is currently available to support an appropriate assessment of the personal protective equipment (PPE) performance requirements in firefighting and emergency medical services (EMS) response. Additionally, there are no existing studies on the potential effects of heat strain on firefighters while wearing ballistic vests with turnout gear. The gap in understanding how to wear ballistic vests in combination with a turnout suit is an important motivation for the proposed project. This study is compounded by the differences in physiological responses between male and female firefighters wearing ballistic vests with firefighter gear. Most fire departments and ASTM E3348 recommend wearing a ballistic vest underneath a turnout suit to protect the gear from heat that can melt or degrade the materials and components used in its construction [9]. Whereas our local fire department recommends wearing ballistic vests over turnout suits. These examples of conflicting approaches to wearing ballistic vests with turnout suits underscore the need for a scientifically considered study of the effect of gear configuration on physiological heat strain and their effects on work performance.

1.1 Background

Reports of bullet injuries to firefighters and emergency medical technicians (EMTs) are often found in media reports and firefighter periodicals. According to the U.S. Fire Administration, among 26,959,000 emergency calls to fire departments only approximately 4% of the calls in 2020 were related to live fire, and 64% of the reported calls to fire departments were associated with a wider range of non-fire scenarios, including mass shootings, medical emergencies, hazardous materials, search and rescue operations, and civil unrest. Police officers and firefighters are often required to work together, but their lack of specialized training and equipment prevents them from entering each other's high-risk sectors. The capacity of police personnel to respond to hostile occurrences may be hindered by visibility problems caused by fire and heat injury. On the other hand, firemen are not equally prepared for situations involving fire and weapons. As a result, it might be challenging for firefighters to execute combined operations when multiple threats are present. Between 2019 and 2025, 130 incidents occurred in the USA where firefighters were shot and killed while responding to non-fire scenarios [7]. Therefore, firefighters must be appropriately equipped with proper ballistic gear to execute multidisciplinary missions. Ballistic vest use, however, may cause thermal discomfort and limit the mobility of the wearers. Firefighting turnout suits are multilayered and heavy. On the other hand, currently, existing ballistic vests for firefighters are also constructed with multi-layered woven or laminated fabrics. Also, the materials used in the construction of the ballistic vests make them heavy, stiff, and non-breathable which impedes proper ventilation of the metabolic heat and moisture through the fabric to the environment. Six firefighting gears in conjunction with ballistic vests were tested to evaluate thermal insulation, evaporative resistance, and total heat loss. The results showed that after adding ballistic vests to the firefighting gear, there was a significant increase in thermal insulation and evaporative resistance which resulted in a significant decrease in total heat loss in the torso area. The thermal insulation evaporative resistance values were used in thermal modeling and the results showed that after adding ballistic vests, the physiological responses (core temperature, mean skin temperature, and cardiac output) were significantly higher than non-ballistic ensembles. Therefore, wearing ballistic vests in conjunction with turnout gear might increase the protection of firefighters in emergencies but it will add a thermal burden causing heat strain and affecting the wearer's performance as well. To contribute to firefighter safety filling gaps in the available information is needed by firefighters for the selection and use of PPE for ballistic protection. The purpose of this research is to generate scientific data on the effect of wearing ballistic vests on firefighter heat strain. The research outlines a quantitative approach for assessing heat strain using standardized methods to quantify the thermal and evaporative resistance of clothing ensembles. This study also involves rendering the evaluation of the physiological effects of clothing ensembles before conducting human trials. The findings of this study will help fire departments to make informed decisions in selecting the combinations of clothing that will be comparatively more comfortable for firefighters to mitigate heat-caused health risks and ensure firefighters' wellness.

Although the word “firefighter” signifies people who fight fire, it’s not limited to that specific duty anymore. Nowadays, fire departments have taken on a wide variety of duties. Firefighters, paramedics, and EMTs work closely with the police, and can and have been called to incidents involving shootings, stabbings, and other violent crimes with active threat [5]. Though violence against fire and EMS responders is uncommon, it is not unheard of. The incident at Colorado's Columbine High School on April 20, 1999, marked a turning point in public safety even though it was not classified as a terrorist attack. That day, two teenagers used homemade IEDs and small weapons to launch a multi-hazard attack against a high school [10] . Initially, they were going to explode two 20-pound propane bombs, start a fire in the cafeteria, and shoot the escaping survivors [10]. The plan failed, but by later shooting at the propane bombs, teenagers managed to spark a small fire in the cafeteria that forced the sprinkler system to activate. According to computer modeling, the kids in the cafeteria that day would have been killed and seriously injured in the firestorm and explosion that resulted from the propane bombs being detonated [10]. Before taking their own lives during the attack, the terrorists effectively set off thirty of their explosive and incendiary devices. About one and a half hours after the opening gunshot, SWAT called for firefighting resources to tackle the cafeteria fire. To create an action plan to deal with the potential for further fire spread, an ad hoc firefighting task force was established, consisting of firemen willing to volunteer for the dangerous duty assignment[10]. The attackers used a combination of fire, IEDs, handguns, and long weapons, resulting in 13 deaths and 24 injuries. "Wanton Violence at Columbine High School" was one of the after-action reports released by the US Fire Administration after the Columbine High School attack. The report provided 56 recommendations for strategic improvements within the fire service. The results mentioned waiting for full "all-clear" from law enforcement and employing "stage and wait" procedures for SWAT. To rescue the injured and provide quicker medical attention, the report recommended the creation of police, firefighting, and emergency medical teams [10]. Because of this incident, law enforcement organizations throughout the nation changed their strategies from waiting for SWAT to meet the attacker to sending out the first police officers to arrive in order to combat the shooter and prevent the victims from dying [11]. However, fire and emergency medical services persisted in using their stage and wait tactics [12].

Fire agencies would need years to start modifying their response strategies to the increasingly deadly active shooter and mass casualty occurrences that have become commonplace in America. Arlington County, Virginia, initiated the national efforts to create integrated protocols for coordinated EMS and law enforcement teams after a full-scale practice in 2009 that resulted in a mass casualty because of the EMS's unacceptable delayed response [13]. According to Arlington's RTF guidelines, groups of two to three police officers—front and rear guards—corresponded with several firefighters and emergency medical personnel to assist the victims [13]. In accordance with Arlington's protocols, firefighter RTF members should also wear Kevlar helmets and ballistic protection, such as rifle plates. The police officers escort the firefighters or EMTs into the warm zones (According to NFPA 3000, a warm zone has the potential for a hazard or an indirect threat to life where PPE is included but not limited to ballistic protection equipment[14]), where there is no immediate threat, even though the area hasn't been thoroughly inspected to the point where the police have proclaimed it fully free of any potential threats. This model has proven effective in situations involving active shooters, but it has limits because it does not account for the addition of fire to the threat mix [13].

There are also several incidents where firefighters were shot and killed in emergency situations. For example, in 2008, a 22-year-old firefighter was shot and killed while responding to a vehicle fire in Maplewood, MO [15]. Two police officers were also wounded in that incident. Additionally, in 2012 two volunteer firefighters were shot and killed, and another two injured, in a planned ambush involving an intentional fire in Webster, NY. Also, in May 2019, a Wisconsin firefighter was shot and killed while responding to a medical call. A police officer and bystander also suffered gunshot wounds. In August 2017, firefighters were shot during a “routine” medical emergency in Charleston, WV [16]. In February 2019, six people, including the shooter, were killed and six others injured in the incident at Henry Pratt Company in Aurora, IL. Furthermore, on June 9, 2020, in Caldwell County, TX, an 18-year-old volunteer firefighter was shot and killed while responding to reports of smoke [17]. Also, in February 2024, two police officers and one firefighter were shot dead after responding to a domestic incident in Minnesota [18].

Since firefighters are no longer exclusively responsible for combating fires and their role has expanded to the cooperation with law enforcement to respond to medical emergencies, violent crimes, and situations with active threats, such as shootings and stabbings, it puts them in a higher chance of experiencing violence. The incidents indicated the growing importance of including ballistic vests as a part of firefighter’s PPE in response to the growing risk of violence they encounter in emergency circumstances. After firefighters became targets of violence, fire departments prompted funds to make ballistic vests standard PPE in the department. The need to keep first responders safe while they protect the public has prompted other departments to consider similar purchases, especially following the civil unrest around the country in the wake of George Floyd's death in Minneapolis. After a shooting incident in Charleston (WV), in 2017, all firefighter and paramedic were provided with ballistic vests. Charleston Fire Department spent $600,000 on 170 ballistic vests, which were customized to fit their sizes [19]. In 2019, the Aurora Fire Department in Illinois purchased 60 vests and helmets for its members months after an active shooter situation in the city [20]. In 2023, new ballistic vests and helmets were distributed to 17 fire departments throughout Wake County in North Carolina [21]. The incidents indicated that there is a need to deploy ballistic vests for firefighters in emergency situations, even though it might cause a physiological burden to them. Therefore, ensuring their physiological comfort with extra protection is crucial.

1.2 Research Aim

The research utilized a quantitative approach for assessing heat strain using standardized methods to quantify the thermal and evaporative resistance of clothing ensembles. This study also involves rendering the evaluation of the physiological effects of clothing ensembles before conducting human trials. The findings will help fire departments to make informed decisions in selecting the combinations of clothing that will be comparatively more comfortable for firefighters to mitigate heat-caused health risks and ensure firefighters' wellness.

The aim of this study is to contribute to firefighter safety by generating scientific evidence on the impact of wearing ballistic vests on firefighter heat strain as well as to fill knowledge gaps needed by firefighters for the selection and use of personal protective equipment (PPE) for ballistic protection for optimal performance during their work.

CHAPTER 2

LITERATURE REVIEW

2.1 Thermoregulation and thermal properties of protective clothing

Humans are homeothermic. Through thermoregulation, humans can maintain a stable body core temperature [22]. However, the thermal balance of the human body is significantly impacted if the metabolic heat is high and heat transfer from the body to the environment is impeded [23]. The human body starts to malfunction and results in thermal heat-illness when the core body temperature exceeds 39°C [24], [25]. Therefore, thermal discomfort emerges when the amount of heat generation in the body exceeds the body's heat dissipation capacity. This discomfort may cause heat illness when the increased metabolic heat production of the body through physical activities combines with highly insulative clothing [26]. Heat strain may limit thermal regulatory responses and, therefore, affect the wearer's work efficiency and physical performance. More serious heat illness conditions such as dehydration, heatstroke, and lack of cognitive power may follow [27]. Thus, heat illness can result in a serious safety issue for the personnel where the primary function of clothing is to create a protective barrier against external hazards.

Developers of protective clothing face a constant challenge of mitigating heat strain experienced by the individuals wearing personal protective equipment. Using personal protective equipment (PPE) can cause wearers significant physiological and physical strain, which can reduce performance, work duration or even cause fatal heat strain. In general, as protection levels increase, the heat strain risks associated with personal protective equipment increase [28][29], [30], [31]. While each layer in a PPE system contributes in a different way to the overall level of protection, all layers also increase the risk of heat strain due to increased evaporative and thermal resistances and increased metabolic heat production associated with the mass of the PPE [28].

Therefore, non-breathable ballistic vests which are primarily designed to provide ballistic protection increase thermal insulation and resistance to evaporative cooling from the human body [32]. Wearing ballistic vests in conjunction with firefighters' turnout gear might increase the risk further. As a result, it might deteriorate working efficiency and increase the risk of heat illness for the firefighters [33], [34], [35]. Therefore, it is mandatory to mitigate the heat strain and ensure the thermophysiological comfort to the firefighters. Thermophysiological comfort is an essential element of the clothing system [36]. Thermal resistance and evaporative resistance are the two principal parameters for measuring the thermoregulations or thermophysiological comfort of protective clothing [28].

2.1.1 Thermal resistance

Thermal resistance or insulation measures the ability of a material or system to reduce the transfer of heat. This term is applied in both engineering and clothing (e.g. thermal insulation in protective clothing). According to ASTM F1291, thermal resistance can be described as the measurement of the resistance to dry heat transfer from a heated body to a relatively calm, cool environment [37]. A high value of thermal resistance indicates the reduction heat transfer from the surface of the body to the environment. However, there is a distinction between the thermal resistance of fabrics and clothing ensembles. Thermal resistance of the fabrics can be referred to as the insulation of the individual materials used in garment without the consideration of how it will be used in a garment [38]. Thermal resistance of the fabrics is associated with fiber composition, weave structure, thickness, and moisture management capabilities [39]. On the other hand, thermal resistance of clothing refers to the complete ensemble of garments including layers and accessories (e.g., gloves, helmets, etc.). Clothing insulation takes into account a number of variables including air gaps between clothing layers, air layers adjoining outer surface of the clothing, fabric thickness, and overall impact of all pieces in the clothing ensemble [38].

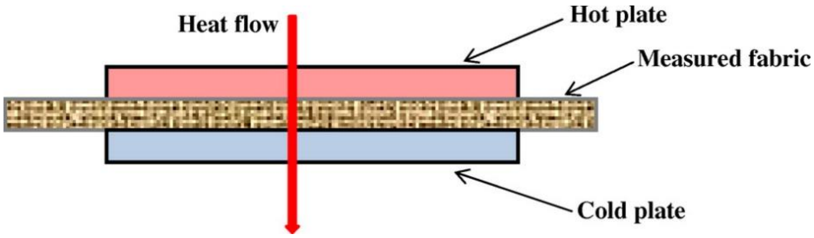


Figure 1. Thermal resistance measurement of fabrics [38]

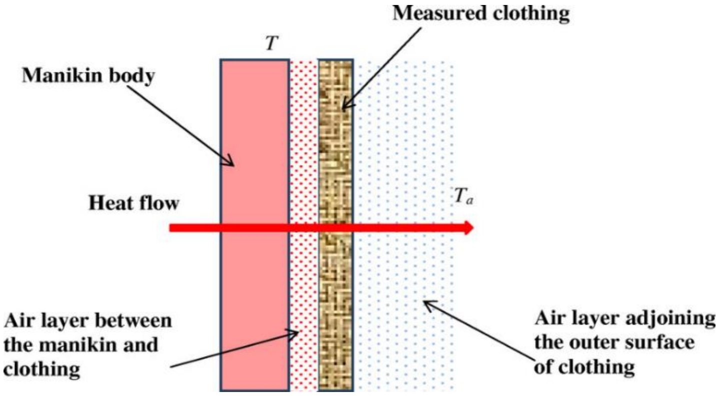


Figure 2. Thermal resistance measurement of clothing [38]

Thermal resistance can be expressed as the formula below

$$R_t = \frac{T_s - T_a}{\frac{Q}{A}}$$

Where R_t = Thermal resistance of clothing and air layer in m^2 °C. W^{-1} or Clo (1 Clo = 0.155 $m^2 \cdot °C \cdot W^{-1}$)

T_s = Temperature of test surface in °C

T_a = Temperature of air layer in °C

Q= Power required to maintain the test surface temperature (W)

A= Surface area of test section in m^2

When total thermal insulation is defined in “Clo” value, the unit resembles the thermal resistance of the clothing worn by a person who feels thermally comfortable sitting in a ventilated room with an ambient temperature of 21°C, a windspeed of 0.1 m/s, and 50% relative humidity[40].

Air and fibers contribute to clothing materials. The amount of air trapped in the majority of clothing materials is far more than that of the fibers. The thickness of the material greatly affects the insulation [41]. With the exception of textile fabrics with exceptionally low densities, the convective component of heat transmission may mostly be disregarded [42]. For a temperature differential of 100 K across the fabric, the radiation component of thermal conductivity only accounts for around 5% of the overall thermal conductivity [43]. The primary method of heat transport via materials is conduction. Therefore, thermal resistance can be calculated using the formula below:

$$R_t = R_{cl} + \frac{1}{f_{cl}(h_c + h_r)} = R_{cl} + \frac{1}{f_{cl}} R_a$$

Where,

R_t = total thermal resistance of the ensemble in $m^2 \cdot °C \cdot W^{-1}$ or I_t in Clo (1 Clo= 0.155 $m^2 \cdot °C \cdot W^{-1}$)

R_{cl} = ensemble intrinsic thermal resistance in $m^2 \cdot °C \cdot W^{-1}$

f_{cl}= clothing area factor, ratio of the clothing surface area to body surface area

h_c = convective heat transfer coefficient in $W \cdot °C^{-1} \cdot m^{-2}$

h_r = radiative heat transfer coefficient in $W \cdot °C^{-1} \cdot m^{-2}$

R_a = thermal resistance of the boundary air layer in $m^2 \cdot °C \cdot W^{-1}$

2.1.2 Evaporative resistance

The latent heat of perspiration that evaporates from the skin is transferred to the environment, resulting in evaporative heat exchange [44]. The difference in vapor pressure between the skin and the surrounding air, as well as the clothing's resistance to moisture transfer, determine how much heat is transmitted. According to ASTM F2370, evaporative resistance can be described as the measurement of resistance to evaporative heat transfer from a heated body to the environment [45]. The higher evaporative resistance of a garment indicates less moisture transfer or greater humidity inside the garment [46]. To assist in the regulation and maintenance of the thermophysiological balance, it is vitally important to determine the combination of clothing that aids heat and moisture transfer.

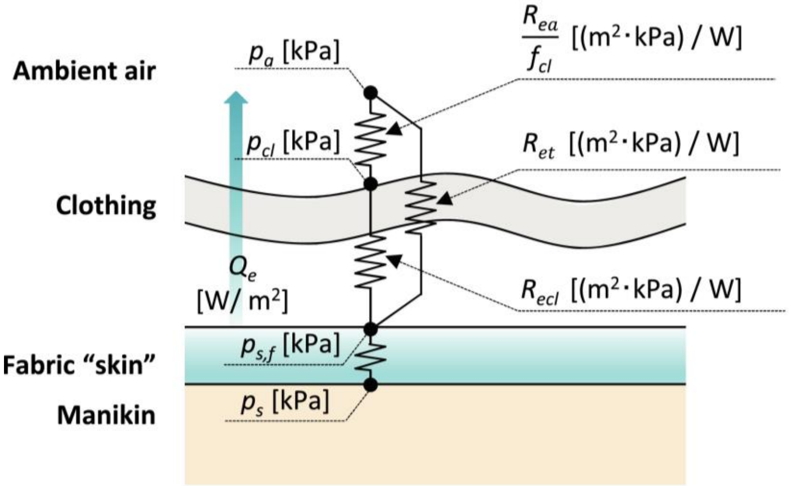


Figure 3. Measurement of evaporative resistance [47]

Evaporative resistance can be expressed as below,

$$R_{et} = \frac{P_s - P_a}{\frac{Q}{A} - [\frac{T_s - T_a}{R_t}]}$$

Where,

R_{et} = ensemble total evaporative resistance in $m^2 \cdot Pa \cdot W^{-1}$

P_s = Water vapor pressure at the test surface in Pa

P_a = Water vapor pressure at the ambient air in Pa

Q = Power required to maintain the test surface temperature (W)

A = Surface area of test section in m^2

T_s = Temperature of test plate in °C

T_a = Temperature of air layer in °C

R_t = total thermal resistance of the ensemble in $m^2 \cdot °C \cdot W^{-1}$ or I_t in Clo

The main factor influencing garment vapor resistance for both normal and permeable textiles is material thickness [41]. The evaporation resistance of textile textiles can be significantly influenced by these components when coatings or membranes are added [48]. There is also another formula to calculate evaporative resistance

$$R_{et} = R_{ecl} + \frac{1}{f_{cl}. h_e} = R_{ecl} + \frac{1}{f_{cl}} R_{ea}$$

Where,

R_{et} = ensemble total evaporative resistance in $m^2 \cdot Pa \cdot W^{-1}$

R_{ecl} = ensemble intrinsic evaporative resistance in $m^2 \cdot P_a \cdot W^{-1}$

f_{cl}= clothing area factor, ratio of the clothing surface area to body surface area

h_e = evaporative heat transfer coefficient in $W \cdot m^{-2} \cdot Pa^{-1}$

R_{ea}= evaporative resistance of the boundary air layer in $m2 \cdot Pa \cdot W^{-1}$

2.2 Assessment of thermal and evaporative resistance

There are three primary methods to assess the thermal and evaporative resistance of a textile fabric or garment- sweating guarded hotplate, sweating thermal manikin, and human subjects [49]. Studies showed that thermal manikin measurement yields a more realistic value than a sweating-guarded hotplate [50] [51] [52], [53]. Thermal manikin can assess the impact of clothing's boundary air layers and investigate the role that multiple layers play in the evaporative resistance of clothing. Thermal manikin also measures the steady-state rate of evaporative heat loss and the water vapor pressure differential between human skin and ambient air [49]. Therefore, to accurately evaluate the thermal comfort of clothing and the environment, sweating thermal manikin is a vital tool for understanding heat exchange between the human body and the environment. By correctly measuring the heat exchange between the human body and its surroundings, the thermal comfort of the human subject in the environment may be anticipated based on human physiology by using sweating thermal manikin.

There are several types of thermal manikin. Among them Newton thermal manikins are all over the world which was manufactured by Measurement Technology Northwest in the United States. Newton was designed in accordance with ASTM and ISO standards to meet the objectives of clothing evaluation research [54]. Since Newton is articulated and has an outside shell composed of carbon-epoxy heat conductive materials, it allows each joint to move and different human body positions can be achieved. Several researchers examined the efficiency of Newton in various labs. The same Newton manikin was used in the laboratory in different countries or regions to test the identical apparel. The findings demonstrated that Newton has a high precision and low variability [54].

To assess the thermal comfort of women's garments male manikins have been used which might lead to the inaccurate findings due to the different body shapes between males and females in terms of sweating accumulation and heat response [54]. Liz is the newest member in the thermal manikin family. Liz also conforms to different ASTM and ISO standards. A thermally conductive carbon-epoxy shell with integrated heating and sensor wire components is used for developing the manikin. Numerous body postures are attainable with complete articulation at the elbows, shoulders, hips, knees, and ankles. To guarantee precise morphology and repeatable manufacturing, 3D CAD modeling was employed to construct Liz [55].

2.2.1 Measurement principle of thermal manikin

Human body heat dissipation occurs primarily in two ways: wet heat loss caused by a gradient in humidity and dry heat loss caused by a gradient in temperature. The total heat dissipation can be expressed as below

Total heat loss (THL) = Dry heat loss + Wet heat loss [54]

Dry heat loss usually occurs through conduction, radiation and convection. On the other hand, wet heat loss occurs by evaporation [56]. THL can be calculated according to ASTM F1868 (part C) by measuring thermal resistance (R_t) and apparent evaporative resistance (R_{et})[57] .

Predicted total heat loss by the thermal manikin can be calculated by using the formula

$$Q_{manikin} = \frac{T_s - T_a}{R_t} + \frac{P_s - P_a}{R_{et}}$$

Where R_t = Thermal resistance of clothing and air layer in m^2 °C. W^{-1} ; T_s = Temperature of test plate in °C; T_a = Temperature of air layer in °C; R_{et} = ensemble total evaporative resistance in $m^2 \cdot kPa \cdot W^{-1}$; P_s = Water vapor pressure at the test surface in kPa; P_a = Water vapor pressure at the ambient air in kPa

Thermal manikin measures both local and whole-body heat fluxes as well as evaporative resistance and thermal insulation of clothing which imitates the heat exchange between the environment and the human body. The complex physiological responses to temperature changes in the environment that humans experience, such as shivering, vasomotion, and sweating, can be replicated by the thermal regulation manikin. A thermal manikin that is regulated by a thermal physiological regulation model through a feedback loop is part of the thermal regulation manikin. The thermal manikin is designed to react to the temperature as an actual human. The surface temperature of thermal manikin is measured by resistance wires embedded in the outermost protective coating [58]. The heating wires or foils are located on the inner side of the manikin shells. The thermal manikin is generally heated to a given constant and homogeneous surface temperature, and the power input to maintain this temperature is used to calculate the resultant heat loss from the manikin surface. Therefore, the heat fluxes measured by the manikin are used as feedback representing the amount of heat exchanged with the environment in the present climate and clothing conditions [58]. Using the heat flux measurements, thermal insulation and evaporative resistance are measured by thermal sweating manikin. When more heat flux is required to maintain a specific surface temperature of thermal manikin, is indicates there is a more heat loss, therefore, less insulation or resistance of the clothing system and vice versa. Thermal manikin can be used as an extremely effective tool to measure the thermal insulation and evaporative resistance of different firefighting clothing ensembles.

2.3 Firefighting Turnout Ensemble

The firefighter turnout ensemble is designed to protect the firefighters from multidimensional hazards such as thermal and chemical exposures, biological contaminants, and sharp objects [59]. The primary consideration for firefighting protective clothing is to ensure thermal protection against external heat [60]. Therefore, the thermal barrier of the turnout clothing adds bulkiness and creates a barrier to metabolic heat and moisture transfer from the body to the environment. A conventional firefighter turnout outfit includes a coat, pants, hood, gloves, and boots. The turnout suits are comprised of three-layers composite system: the outer shell, moisture barrier, and thermal liner [61]. According to NFPA 1971, these three layers are required to construct safe gear for firefighters. Therefore, it is crucial that each layer of the firefighting turnout suit works well together to serve balanced protection.

Figure 4. Standard firefighting turnout gear

The outermost layer of the composite system that exhibits fluorescent reflective materials, patches, and pockets is the outer shell of the turnout suit. The main function of the outer shell includes resistance to flame, first-line defense against heat, abrasion, and tearing, contributes to the overall weight of the garment, and impacts flexibility and durability. Typically, outer shells are composed of woven textiles with a water-repellent coating and blends of naturally flame-resistant fibers, including polyaramid, polybenzimidazole (PBI), and polybenzoxazole (PBO) [62].

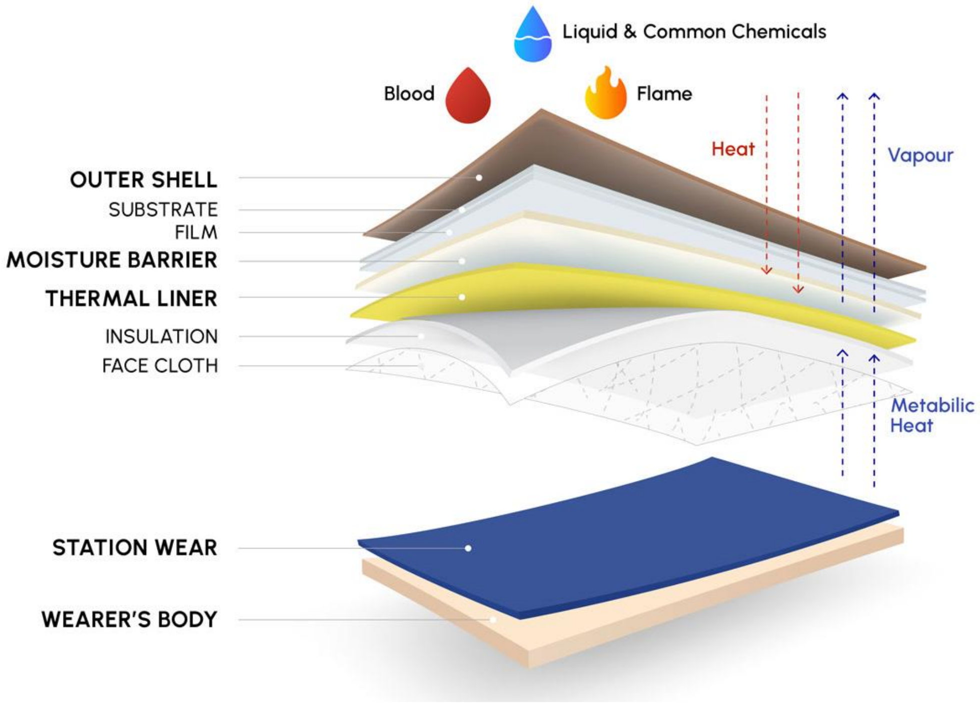


Figure 5. Graphic of the multiple essential layers of a fire suit, each with different protective qualities [63]

The moisture barrier is the protection layer found in the middle of the composite system. This semi-permeable layer prevents chemical, liquids, and bloodborne pathogens from penetrating through the turnout suit while still allowing the sweat vapor transmission from the body to the environment [64]. The majority of moisture barriers are composed of a fire-resistant base fabric laminated to a thin, semi-permeable membrane. The evaporative resistance of firefighting composites is primarily determined by moisture barriers [65], and it can be divided into three groups: porous, non-porous hydrophilic, and combined porous-nonporous membranes [62].

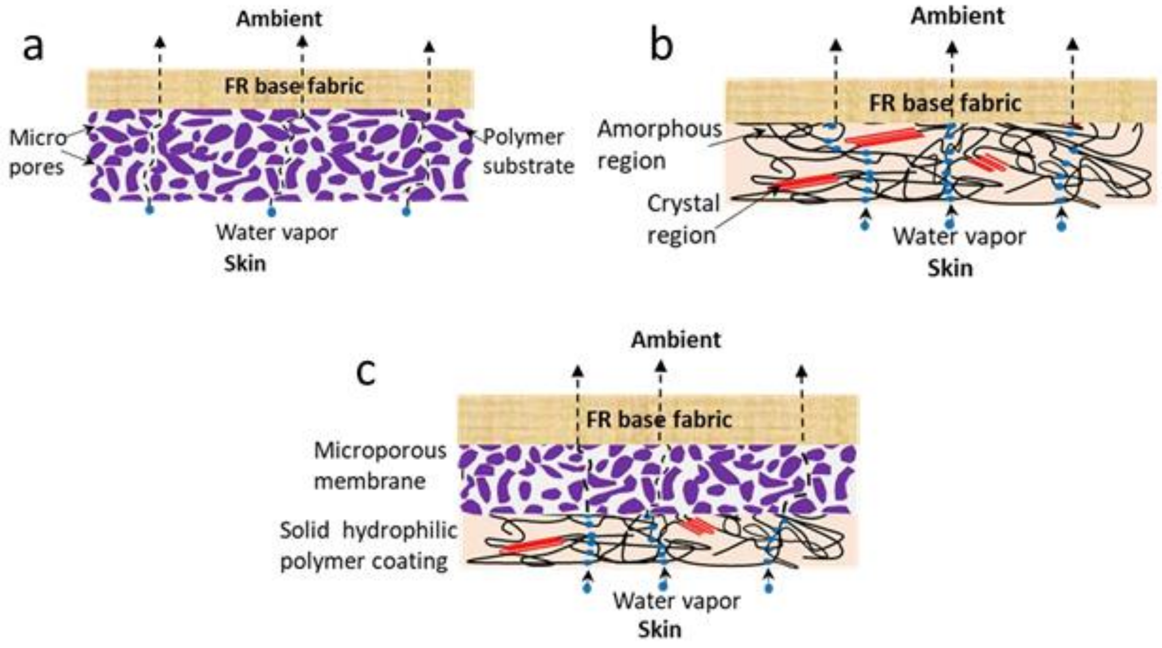


Figure 6. Water vapor diffusion through (a) porous, (b) non-porous hydrophilic and (c) combined porous-nonporous moisture barrier membranes[56]

In most cases, porous Gore-Tex polytetrafluoroethylene (PTFE) membrane is used as a moisture barrier in a bicomponent structure with an air cushion created by polyurethane (PU) [62]. The thermal liner is the innermost layer within the composite system that is worn closest to the skin. It plays a crucial role in wicking moisture and taking sweat away from the body. This layer needs to permit the release of metabolic heat in order to prevent too much heat from accumulating in the turnout gear and avoid heat strain. [66]. Usually, thermal liner contains a nonwoven batting attached to a facecloth (combination of aramid, para-aramid, viscose, polyamide, and nylon fibers) [62]. Thermal liner is the most critical component of firefighting turnout suit as the thermal protection and heat strain is impacted by it [62].

Turnout gear provides protection against numerous risks such as heat and flame, steam, chemicals, blood-borne infections, and sharp objects because of its multi-layer structure and design. The body's capacity to dissipate heat efficiently is diminished when numerous layers of fabric and garments are worn together in a single clothing system because it increases fabric thickness and creates microclimate air gaps [67]. For example, in a study by Lee (2013) , the nude body had a thermal resistance of 0.8 Clo. The evaluated summer ensembles range in whole-body garment insulation from 0.22 to 0.57 Clo; spring and fall range from 0.53 to 0.80 Clo. winter clothing had a thermal insulation from 0.8 to 1.4 Clo. On the other hand, for military uniforms with ballistic vests , thermal insulation ranges from 1.02 to 1.20 Clo [68] ; for firefighters turnout suit, thermal resistance ranges from 1.5 to 1.6 Clo [69]. Therefore, the Clo values of different clothing indicated that with the addition of clothing layer, thermal resistance increases. Additionally, evaporative resistance in $m^2 \cdot Pa \cdot W^{-1}$ for nude body is 13, for station uniform 28, and for firefighter’s turnout coverall (worn over station uniform) with gloves and socks is 62 [70].

2.3.1 Effect of firefighter turnout suit on heat strain

Over the past few decades, different polymer-based fibers with thermal protective properties such as aramid (e.g. Nomex, Kevlar), polyamide-imide (e.g. Kermel), polyimide (e.g. Lenzing), and polybenzimidazole (e.g. PBI) have been used for the construction of firefighters' gear [71]. Although these advanced heat-resistant fibers are commonly used in turnout suits to provide protection against extreme heat and flames, they can contribute to heat strain. The high insulation property of these high-performance fabrics causes reduced heat dissipation and limited moisture evaporation. These materials also add bulk to the turnout suit causing physical strain. The added mass, along with the high insulation, increases the need for cardiovascular activity and causes fatigue, exacerbating heat strain [44], [72]. Additionally, firefighters frequently perform pushing, pulling, holding, turning, wielding, tossing, and lifting tasks, all of which have the potential to cause overexertion [73]. Currently available turnout suits in the market offer significantly more thermal insulation than is required for most of the duties that firefighters conduct. Between 80% and 90% of a firefighter's working time is negatively impacted by excessive garment insulation in their turnout suit [52], [74]. Many studies have examined the influence of heat on athletic performance over the years, but fewer examined the direct effects of higher ambient temperatures on physical performance in occupations that require manual handling [75]. Researchers using descriptive field methods have studied firefighters working in a range of environmental circumstances. However, it is challenging to quantify the impact of heat strain on work performance and physiology precisely due to the lack of a control group and the non-standardization of work tasks in the field. Furthermore, an incumbent worker's production may be dictated by a variety of highly variable conditions, including temperature, humidity, wind, and the severity of the emergency situation [75]. No existing study has a protocol that includes the work intensities, durations, work to rest ratios, and activity modes that constitute firefighting tasks in emergency situations.

Although the primary purpose of firefighter turnout suits is to protect the firefighters from external thermal influences, it cannot dissipate metabolic heat released by evaporation of sweat through the layers of the clothing. Therefore, the heat is retained in the area between the firefighter's body and the layers of turnout suits. The materials used in the construction of turnout gear lack breathability which also causes heat strain to the firefighters [76]. Additionally, there are other factors that hinder the rate of evaporation of sweat of the firefighters such as hot and humid weather [44] and weight and thickness of the garment [77]. When the garment weight and thickness increases, the metabolic rate increases [77], [78] [79][80]. Therefore, it causes more metabolic heat production and sweating which negatively impacts the comfort of the firefighters resulting in heat strain. To certify firefighters' turnout gears, the American Society for Testing and Materials (ASTM) F1868 performance standards and the National Fire Protection Association (NFPA) 1971 require the evaluation of total heat loss and evaporative resistance [61], [81].

A survey study by Barker et al., [82] found that a short-sleeved t-shirt with long pants is the most commonly worn garment (44.6%) when firefighters are in the fire station. In case of an emergency, they wear firefighter turnout gear on top of the station uniform. When they are called in an active shooter scenario, they wear ballistic vests on top of turnout suits [83]. Apparently, it is important for firefighters to add more layers in their clothing to enhance protection but at the same time it compromises comfort. The survey study by Mica et al., [83] demonstrated several combinations of clothing ensembles worn by firefighters such as ballistic vests worn with station uniform (over), and ballistic vests worn with turnout suits (over or under). The study [83] indicated that there is a need for scientific studies that will assess several combinations of firefighter turnout suits, and the effect of heat strain caused by clothing.

The combination of strenuous physical work, extreme temperatures, and heavy protection gear causes physiological strains during firefighting operations [84]. The protective gear worn by firefighters, in particular, increases the metabolic rate because of the additional weight carried by the clothing and prevents body heat from dissipating from the skin into the surrounding air . For example, turnout gear for firefighters typically is heavier [85] and has greater thermal insulation [69]. The protective gear worn by firefighters increased the metabolic rate by 15 W/m^2 at rest and by 115 W/m^2 during intensive work [86]. Compared to conventional clothes, increasing the weight of clothing by 3 or 5 kg increased energy expenses during exercise by 5 and 9%, respectively [87]. Wearing protective garments increased oxygen consumption by 13–18% (mean 9.3 kg) [88].

The different physical tasks and environmental factors that come together to produce the heat load that a person works under are referred to as heat stress. Heat strain is the term used to describe the physiological reaction to this heat stress and the subsequent thermoregulatory mechanisms [89], [90]. Firefighters perform various high-intensity tasks while wearing heavy and semi-permeable protective clothing and equipment. Therefore, significant levels of heat strain may occur during their occupational tasks[91]. The amount of heat strain on firefighters is also dependent on their activity level. Activity level refers to the intensity and frequency of physical movements ranging from sedentary to vigorous activities [92].

Heat strain could cause various heat-related diseases, such as heat stroke, dehydration, and electrolyte imbalance [93] According to the statistics of accidental deaths of firefighters in the USA, the probability of death due to sudden heat-related illness accounts for 88% of mortality [94]. Heat strain emerges when the amount of heat generation in the body exceeds the body's heat dissipation capacity. This discomfort causes heat illness when the increased metabolic heat production of the body through physical activities combines with impermeable clothing [95].

Firefighting turnout suits are multilayered and heavy. On the other hand, currently existing ballistic vests for firefighters are also constructed with multi-layered woven or laminated fabrics [96]. Also, the materials used in the construction of the ballistic vests make them heavy, stiff, and non-breathable which impedes proper ventilation of the metabolic heat and moisture through the fabric to the environment [97]. Therefore, wearing ballistic vests in conjunction with turnout gear might increase the protection of firefighters in emergencies but it will add a thermal burden causing heat strain and affecting the wearer's performance as well. A quantitative study by Potter [98] tested and analyzed the tradeoffs between ballistic protection, thermal burden, and physical work performance using thermal manikin to measure thermal resistance and vapor permeability indexes for a baseline clothing ensemble. The result showed that thermophysiological comfort changes the wearer's physical performance drastically. Therefore, wearing ballistic vests with firefighter gear might cause serious heat strain to the firefighters with the added layers and bulk. Understanding the tradeoff between protection and heat strain is critical to improving firefighter safety and performance during emergency scenarios.

2.3.2 Heat loss through protective clothing

The primary way of dissipating excess heat in the body is sweat evaporation. Wearing clothing slows down the process and high humidity restricts this process further [74]. The body generates heat during physical activity which must escape the body to keep core temperature stable. The wearer may experience heat exhaustion, fatigue, stroke, or even death if this heat cannot manage to evaporate. The incorporation of multi-layered clothing results in air gaps that impede sweat's ability to evaporate into the surrounding atmosphere. In addition to the type of fabric and materials of clothing, humidity also has an impact on perspiration evaporation [74].

According to Bergman (2011), convection is the transfer of mass and heat through a gas or liquid, or in this instance, an air exchange [99]. The ambient temperature must be lower than the suit's microclimate air temperature to stimulate heat loss through convection. The amount of heat exchange increases with the difference in air temperature between the two objects [100]. There are two kinds of convection: forced convection, which occurs due to wind flow or human activity-induced "air pumping," and natural convection, which occurs as a result of existing temperature gradients. Clothes are typically evaluated in a dry, wind-free setting without any movement as a baseline. This eliminates forced convection effects in the presence of wind and the effects of pumping while the body is in motion, such as walking [36]

Sweat evaporation is also a form of heat loss that occurs within the garment system and is a "highly effective" heat transfer method [100]. The body uses this kind of heat loss as a last resort when convection is not adequately capable of removing heat [101], [100]. The body may mostly rely on sweat evaporation to prevent overheating, even in low-temperature conditions when protective clothing is worn [101]. Since the amount of heat lost through sweat evaporation increases as the metabolic rate rises, the wearer would only be completely dry at extremely low work rates [101] .

There is an even higher need for perspiration to evaporate in hot and humid conditions. The body's capacity for evaporative cooling through sweat depends on a number of factors, including the ambient temperature, the wearer's fitness level, the degree of body acclimation, the type of clothing being worn, and the evaporative efficiency of the clothing materials [101]. Increasing the rate of air exchange between the clothing ensemble and the external environment is one method of imparting change and increasing sweat evaporation rate in the clothing system, aside from improving materials [102]. According to Ke, et al., (2014), there are three components to air exchange between a particular area inside a garment and the environment: 1) air exchange between the microclimates that are specific to the body part, 2) air exchange through the fabric layers to the environment, and 3) air exchange through garment apertures with the air outside [103]. The air exchange between the microclimate and the surroundings through clothing openings is the most efficient way for heat loss [103].

2.4 Effects of ballistic vests on heat strain in law enforcement applications

The thermal discomfort of ballistic vests has been an issue of serious consideration for the defense personnel [104]. According to the US Armed Force- Health Surveillance Branch (2024), there were 415 incidents of heatstroke in 2023 and 12,448 incidents of heat exhaustion among US military personnel through 2019 to 2024 [105]. Despite the development of the protection performance of modern ballistic vests, it does not provide adequate thermo-physiological comfort to the wearer [106].

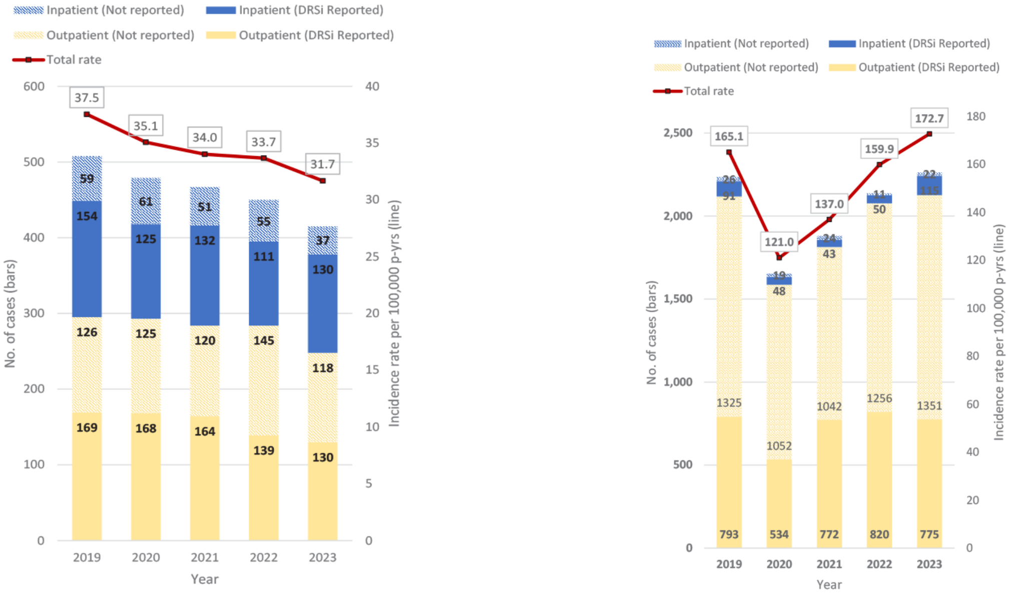


Figure 7. Incidence rates of heat stroke and heat exhaustion (2019-2024)[105]

The effects of ballistic vests on heat strain and physiological responses were investigated under different environmental conditions and activity levels. A study by Dempsey et al., (2013) recruited 53 male police officers and found that wearing ballistic vests significantly increased heart rate, and oxygen consumption of the participants during moderate and high-intensity exercise [107]. Another study by Larsen et al., (2012) evaluated the impact of ballistic vest on 11 male athletes in a simulated high-intensity military tasks and the results showed that there was significant raise in core temperature but no change in heart rate [108]. In a study by Yuan, et al., (2019), five male participants were observed under hot and humid conditions (38°C and RH 60%) where with and without (control) ballistic vest trails were examined for moderate intensity work. The results showed that significant increase in core temperature, mean skin temperature, heart rate, and oxygen consumption during exercise in with ballistic vest trial compared to control trial [109]. Through all the studies, the results consistently demonstrated that ballistic vests contribute to heat strain and physiological exhaustion during physical activity by increasing core temperature and heart rate. However, Pyke et al. (2015) designed a study where eight males were recruited for moderate intensity task in a climate chamber (31°C and RH 60%) wearing no ballistic vests (control) and overt and covert ballistic vests. The results showed that there were no significant changes in core temperature, mean skin temperature and heart rate among control, overt and covert conditions [110]. It indicated that ballistic vests induced substantial heat strain at 38°C and 60% relative humidity [109] but the differences were negligible at 31°C and 60% relative humidity for human studies.

2.4.1 Ballistic vest and threat levels

A ballistic vest is designed to protect the crucial organs in the torso [111]; therefore, it triples the likelihood of survival if a wearer gets shot into the torso (LaTourrette, 2010). Although it is considered one of the most important personal shields for police officers, military, and security personnel (Horsfall, Watson, & Champion, 2013), nowadays it is being used by firefighters in North America [83]. Typically, ballistic vests are available in two forms: hard ballistic vests and soft ballistic vests. A hard ballistic vest is used by military officers to protect against high-speed bullets or projectiles. To provide this functionality, heavy and rigid ceramic and steel plates are used as panels. On the other hand, soft ballistic vests are used for lower ballistic threats such as shotguns, handguns, hand grenades, etc. and these vests are routine wear for police officers and security personnel. A survey results showed that usually soft ballistic vests are used by the fire departments in North America [83].

The soft ballistic vests are usually multi-layered woven or laminated fabric which makes them more flexible and lighter [96]. High-performance fibers are mostly used for the construction of soft ballistic vests. Fiber properties are of utmost importance for ballistic vests. The high-performance fibers used for ballistic vests are glass, aramid (Kevlar, Nomex, Technora, and Twaron), high-density polyethylene (Spectra and Dyneema) and Polybenzoxazole (Zylon) fibers [112] which are woven into plain weave of high areal density and later constructed into a ballistic vest in a multi-layered form [113]. However, soft ballistic vests are still heavy, bulky, and non-breathable due to the stitching or laminating of a large number of layers of fabric which impedes the mobility and agility of the soldiers. It also creates poor fit, thermal discomfort, and negative physical and psychological impacts on the wearers [32], [114].

In general, ballistic vest features an extra panel insert for protection in addition to front and back panels. To alter the length and width of the torso, there are also straps that may be adjusted around the waist and over the shoulders. The threat levels determine the selection of materials, the number of layers on the front and back panels, and the thickness of the supplementary panels. For soft armor, the front and rear panels might consist of multiple layers of bullet-resistant textiles based on aramid yarn layered on top of one another [112]. The average weight of ballistic vests is 5 to 6 kg and thickness are 20 to 25mm [115].

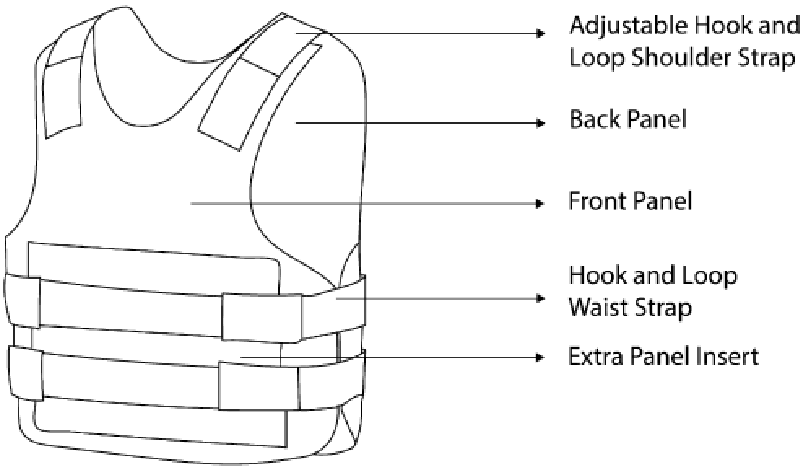
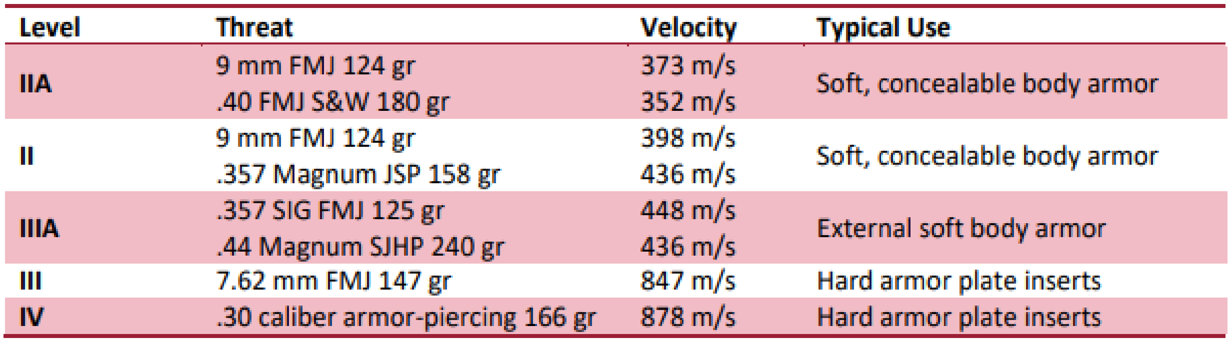


Figure 8. Structure of a basic ballistic vest[112]

Ballistic resistance standards for personal ballistic vests are established by the National Institute of Justice (NIJ) [96] According to market research, firefighter ballistic vests meet NIJ standards and are NIJ-certified [83] . The levels of defense offered by various forms of ballistic vest against specific ballistic threats are indicated by the NIJ threat levels. The NIJ Ballistic Threat Levels IIA, II, IIIA, III, and IV offer increasingly more protection against bullets with higher calibers. These threat levels offer recommendations for choosing the appropriate ballistic vests according to the particular risks that firefighters may face. Although these levels offer consistent classification, other elements that affect ballistic vest performance include fit, design, and the specifics of the whole ballistic system.



Level	Threat	Velocity	Typical Use
IIA	9 mm FMJ 124 gr .40 FMJ S&W 180 gr	373 m/s 352 m/s	Soft, concealable body armor
II	9 mm FMJ 124 gr .357 Magnum JSP 158 gr	398 m/s 436 m/s	Soft, concealable body armor
IIIA	.357 SIG FMJ 125 gr .44 Magnum SJHP 240 gr	448 m/s 436 m/s	External soft body armor
III	7.62 mm FMJ 147 gr	847 m/s	Hard armor plate inserts
IV	.30 caliber armor-piercing 166 gr	878 m/s	Hard armor plate inserts

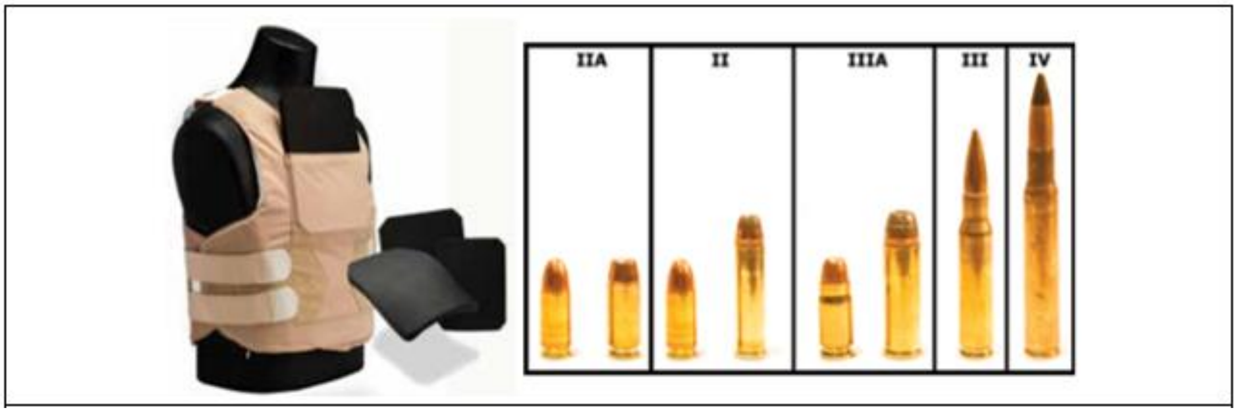


Figure 9. NIJ Ballistic Protection Levels and Associated Test Ammunition[111]

Level IIA, II, and IIIA ballistic vests are used for protection against handgun ammunition. Level III and IV are used for protection against rifles [111]. Despite the development of the modern ballistic vest which offers effective ballistic protection, it does not adequately meet the comfort requirements of the wearer which makes it less likely to be worn.

2.4.2 Ballistic vests for firefighters

Firefighters encounter a bewildering range of options when specifying and procuring body armor. Different categories of body armor provide different levels of protection against firearms. Manufacturers produce ballistic vests specifically for firefighters and EMS personnel, and they offer PPE options for both for law enforcement and non-law enforcement applications. Most commercially available ballistic vests for firefighter use are soft armor and they are NIJ certified [83].

According to the manufacturers, ballistic vests for firefighters are similar in design apart from the fact that they are cut differently around the neck and armhole [83]. For law enforcement officers, the neckline and armhole are cut in a round shape to optimize mobility and protection. For firefighters, the neckline and armholes are cut in a square shape for the convenience of manufacturing as square shaped neckline and armholes are easier to cut and sew than round shape. Round shaped neckline and armhole provide more coverage and range if motions for the law enforcement officers. However, firefighters do not have to move or hold guns in a specific posture, therefore, the square neckline and armhole do not hinder their range of motion and mobility [83].

2.4.3 Scenarios where firefighters need to wear ballistic vests

The deployment scenarios where firefighters use ballistic protective equipment include active shooter (24%), EMS (19%), and civil unrest (16%) (Figure 10). Nine percent of firefighters had never worn ballistic protective equipment [83].

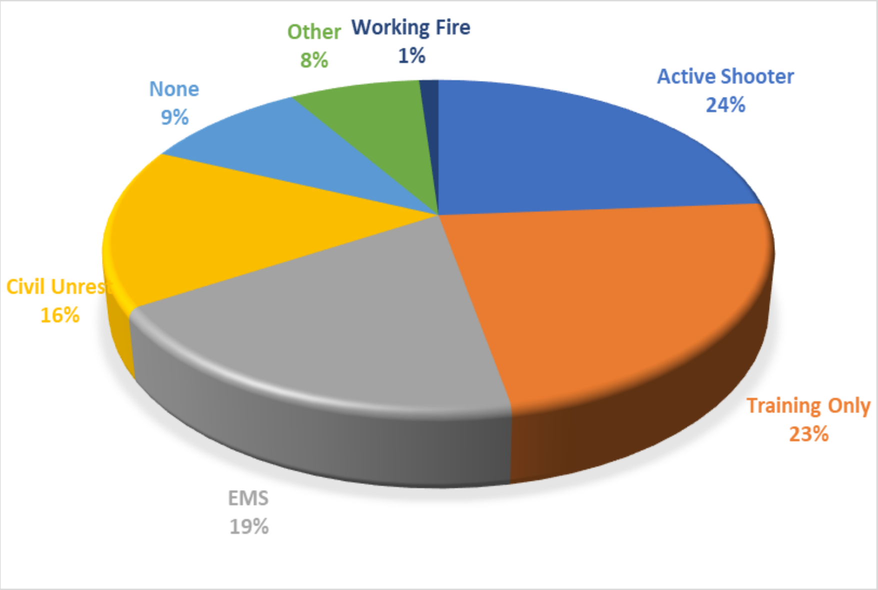


Figure 10. Scenarios where firefighters have worn ballistic protective equipment

In the US, emergency medical services (EMS) are a crucial part of the fire service's operations. The American fire department is ideally situated both geographically and strategically to provide quick, efficient patient care and time-sensitive responses. In practically every American municipality, the fire department serves as the first medical responder for critical illness and injuries [116]. The National Fire Protection Association (NFPA) set consensus response time criteria, which many fire departments in many communities aim to meet. These requirements are four minutes for basic life support and eight minutes for advanced life support [116].

Active shooter situations are unpredictable and evolve quickly. Typically, the immediate deployment of law enforcement is required to stop the shooting and mitigate harm to victims . Civil unrest can happen at times of social unrest, after sporting events, or during periods of heightened community tension. Responding to these situations require calling in fire and emergency medical services (EMS) personnel, who put themselves at higher than anticipated levels of risk. The Office of Emergency Medical Services (OEMS) of the National Highway Transportation Safety Administration (NHTSA) and the U.S. Fire Administration (USFA) put their best effort to help firefighters respond to civil unrest scenarios in the community [117] According to NFPA 3000, there are three zones for civil unrest as following:

Hot Zone
An area considered unsafe. Law enforcement support is required for force protection

Warm Zone
An area of lower threat, but which may become unsafe. Law enforcement support is recommended for entry

Cold Zone
An area of little to no threat of civil unrest or violence. Law enforcement support is optional for entry

Figure 11. Zones for civil unrest[14]

For active shooter, EMS, and civil unrest scenarios, NFPA 3000 provides guidelines for necessary actions and functions related to preparedness, response, and recovery for first responders/firefighters. Ballistic protection equipment (BPE) for fire and EMS personnel should be certified by the National Institute of Justice (NIJ). The ballistic vests should maintain at least NIJ level IIIA according to NIJ Standard - 0101.06. The integrated response team should also consider the use of a ballistic helmet, flashlight, medical exam gloves, an individual first aid kit,etc. PPE & BPE worn externally shall be identified with the agency or responder's role [14].

2.5 Standards for ballistic vests and turnout gear for firefighters

The standards for ballistic vests and firefighting PPE are established by independent organizations that evaluate and test the equipment to ensure it meets certain safety standards. The standards are designed to ensure the safety of firefighters and those who wear ballistic vests. Compliance with these standards is often required by law or regulation and following them can facilitate international trade by ensuring that products meet the requirements of different countries and regions which can help to reduce barriers to trade and increase market access. By adhering to these standards, manufacturers can ensure that their products meet minimum quality requirements. This helps to maintain consistency in product performance and reduces the risk of product failure. For firefighting turnout gear, NFPA 1971, and NFPA 1999 standards are generally followed. For ballistic vests, NIJ 0101.06, and NIJ 0115.00 guidelines are followed. ASTM E3348 and NFPA 3000 standards specifically provide guidelines for ballistic vests for non-law enforcement officers. Standards are constantly evolving to reflect changes in technology and best practices. By reviewing these standards, manufacturers can stay up to date with the latest innovations in their industry.

2.5.1 NIJ Standard 0101.06 (Standard for ballistic vests for law enforcement officers)

Depending on the necessity for protection and the design of the garment, different levels of ballistic and stab protection are offered. The National Institute of Justice (NIJ), which determines protection level classifications and specifies necessary testing processes for body armor, is the most widely acknowledged standard organization for body armor. In Standard NIJ-0101.06 six levels of ballistic protection are outlined- IIA, II, IIIA, III, IV, and Special. Levels IIA and II provide defense against 9mm pistols, with level II providing better defense against faster velocity. With rising velocity (436-448 m/s), Level IIIA shields the wearer against 0.357 SIG and 0.44 Magnum handgun bullets. After Level IIIA, rifles (Type III) and armor-piercing projectiles (Type IV) are stopped with hard armor or plate inserts.

2.5.2 NFPA 1999 & 1971 Standards (Standards on protective ensembles and equipment for firefighters and emergency medical responders)

NFPA 1999 Standard on Protective Clothing and Ensembles for Emergency Medical Operations specifies requirements for protecting EMS personnel from contact with blood and body fluid-borne pathogens. Also, the standard includes some specific testing regarding total heat loss (THL) of the material composite to ensure breathability and thermal comfort; It also includes seam, tear, and breaking strength of each composite layer, flammability, cleaning, shrinkage of the material. The NFPA 1971 Standard established minimum levels of protection for the structural turnout suits firefighters from thermal, physical, environmental, and biological hazards.

2.5.3 ASTM E3348 Standard (a standard guide for body armor for non-law enforcement first responders)

The ASTM E3348 standard provides instructions for ballistic vests worn by non-law enforcement officers. The performance requirements for ballistic vests in this standard are meant to shield the wearer from projectile impacts from bullets and fragments including durability, structural integrity, and ballistic resistance. It provides the guidelines for the selection of the appropriate ballistic vests and usage of ballistic vests with firefighting gear as well. It's crucial to remember that ASTM E3348 is a voluntary standard, which means that producers are free to decide whether to subject their goods to the testing specified in the standard rather than being legally forced to do so. To ensure that the products achieve the maximum degree of performance, many manufacturers also subject their goods to testing with additional standards, such as the NIJ 0101.06. However, ASTM E3348 provides guidelines for when and where to wear ballistic vests for firefighters to ensure their safety. The summary of the guidelines is as follows:

Selection of the appropriate ballistic vests

Responders requiring ballistic vests may be those likely to respond to the following types of situations where firearms are expected or likely to be present, such as those listed below:

1. Acts of violence
2. Mass casualty incidents that could result in ballistic injuries
3. Riots, uprisings, and public gatherings with enormous numbers
4. Cases of known violence against public safety personnel at a flagged location, in a family conflict, in domestic violence cases, or in situations involving domestic violence.
5. Suicide involving a known or suspected use of a handgun or a blade
6. Assisting law enforcement at violent crime sites or welfare checkpoints
7. Investigation of arson

8. Both active and staged warm zone operations (including rescue task force response)

The top management of the department should evaluate potential risks, identify them using a risk assessment specific to their agency, and determine which employees need ballistic protection.

1. It might be required to provide certain employees with personal body armor that they must regularly wear as a part of their duty uniform.

2. It might be appropriate to provide shared ballistic vests. They should be stored until needed and worn by several people to additional staff members. It is recommended that shared body armor be kept in specific areas with regulated environmental conditions.

Firefighter Guidance for Ballistic Vests Use with Turnout Gear

ASTM E3348 provides guidelines for wearing ballistic vests with turnout gear for firefighters. The summary of the guidelines is as follows:

1. Avoid wearing body armor with turnout gear.
2. Studies should be done to determine whether the added ballistic protection from ballistic vests when worn with turnout gear has a detrimental effect on heat stress.
3. Another alternative might be for firefighters to wear less strenuous flame-resistant clothes instead of turnout gear if a ballistic vest is required.
4. To avoid component damage or melting, body armor must be worn underneath turnout gear when worn with it.
5. Polyester and other flammable, thermally conductive materials might be used in body armor, which could affect the wearer.

2.5.4 NFPA 3000 (Standard for an active shooter/hostile event response program)

NFPA 3000 provides necessary actions and functions related to preparedness, response, and recovery from an active shooter/hostile event response for first responders. The standard provides guidelines for ballistic protection for firefighters and emergency medical services employees. The guidelines are as follows:

1. BPE should be National Institute of Justice (NIJ) certified
2. Should maintain at least NIJ level IIIA according to NIJ Standard - 0101.06
3. The integrated response team should also consider the use of a ballistic helmet, flashlight, medical exam gloves, an individual first aid kit, etc.
4. PPE & BPE worn externally shall be identified with the agency or responder role.
5. BPE care, maintenance, and replacement should follow NIJ Standard - 0101.06

2.5.5 Gaps of standards

Although ASTM E3348 suggests not wearing ballistic vests with turnout gear, it does not provide an appropriate guideline with possible solutions or any suggested ensemble. Also, the standard suggests wearing ballistic vests underneath the turnout gear which is self-contradictory since they suggested avoiding wearing turnout gear with ballistic vests. However, a survey [83] showed that firefighters wear ballistic vests over the turnout gear. Additionally, the standard also encourages determining whether the added ballistic protection from ballistic vests when worn with turnout gear has a detrimental effect on heat stress. Therefore, it is crucial to determine which combination of ensemble is the best for the firefighters for thermal comfort. Based on the gap in the standards and lack of existing scientific studies on the thermal effect of wearing firefighting turnout gear with ballistic vests, our study proposes identifying and quantifying the specific thermal strain caused by wearing ballistic vests with standard firefighter gear. The primary goal is to generate evidence-based insights which could inform safety policies and operational suggestions for firefighters who may need to wear ballistic PPE (personal protective equipment) in emergency situations.

2.6 Physiological responses to heat strain

2.6.1 Human physiology and heat strain

Body temperature is one of the fundamental variables of the human body that is regulated by a complex control mechanism of thermoregulation. Thermoregulation is a physiological process that permits the body to retain its core temperature within a narrow and optimal range [118]. In this process, the balance between heat production and heat dissipation regulates body temperature. Core temperature (T_{re}), cardiac output (CO), and mean skin temperature (T_{skin}), sweat production and shivering are vital physiological responses to heat strain[119] .

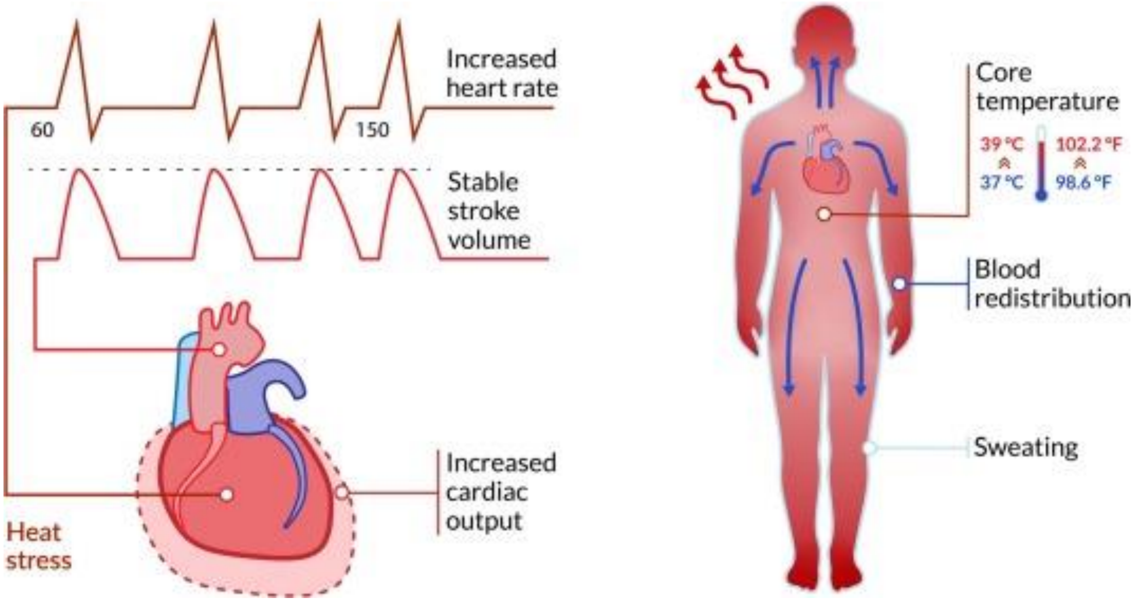


Figure 12. Physiological responses to heat strain[120]

2.6.1.1 Effects of heat strain on core temperature

Core temperature is a direct measure of the body's internal thermal state with the body aiming to maintain a temperature (T_{re}) of between 36.5 to 38.5°C to ensure proper functioning of the body, especially, brain, heart and muscles [121]. The human body usually retains a stable temperature by balancing heat loss and internally generated heat through complex metabolism and neural mechanisms [122]. However, the temperature is not constant throughout the body. For example, the core temperature is usually around 37 °C, and skin temperatures may range from 31.5 ° C to 35.0°C [121], [123]. During physical activities, a person's core temperature can rise to 39° C [25] Although firefighter turnout gear and ballistic vests are necessary to protect human body from external threats, they further increase heat load and exertional strain due to their insulative properties. Studies indicated that the core temperature of firefighters increases to 39° C or higher. Heat related fatal injury can occur when core body temperature rises closer to 40° C [124].

2.6.1.2 Effects of heat strain on skin temperature

When the core temperature increases, the body increases its blood flow to the skin to dissipate heat through sweating evaporation, and radiation and there is an elevation of skin temperature under heat strain. There are four mechanisms for thermoregulation: sweating, shivering, vasodilatation, and vasoconstriction. Sweating causes more perspiration to evaporate, which raises body heat loss. Shivering is an involuntary movement that generates heat. The changes in blood vessel diameter can be referred to as vasodilatation and vasoconstriction, which affect skin temperature by changing the rate of blood exchange with the interior. Heat transfer from the internal organs of the body to the skin is facilitated in the heat by increased conductance beneath the skin's surface (caused by increased blood flow). The heat is then transferred from the body's surface to the surroundings by sweating convection and evaporation [123].

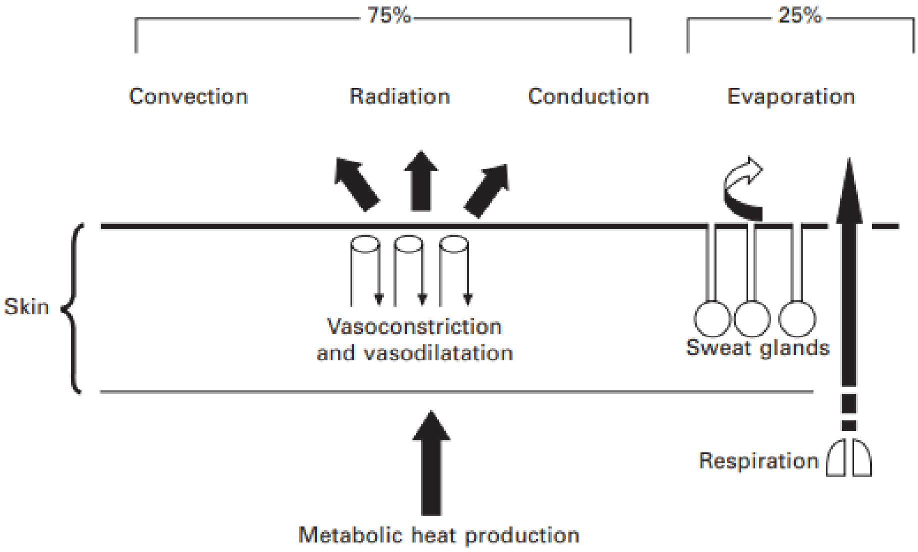


Figure 13. Metabolic heat exchange with environment through and above skin[123]

When wearing protective clothing, the human sweat travels through clothing on its way from the skin to the environment. Therefore, the addition of clothing layers creates a barrier to dissipating metabolic heat through the clothing. Since the human body always performs to maintain thermal balance, the addition of protective clothing layer makes the human body work harder to evaporate the sweat through the layers of clothing and causes heat strain exhaustion [28]. The heat transfer through and above skin and clothing can be represented as below

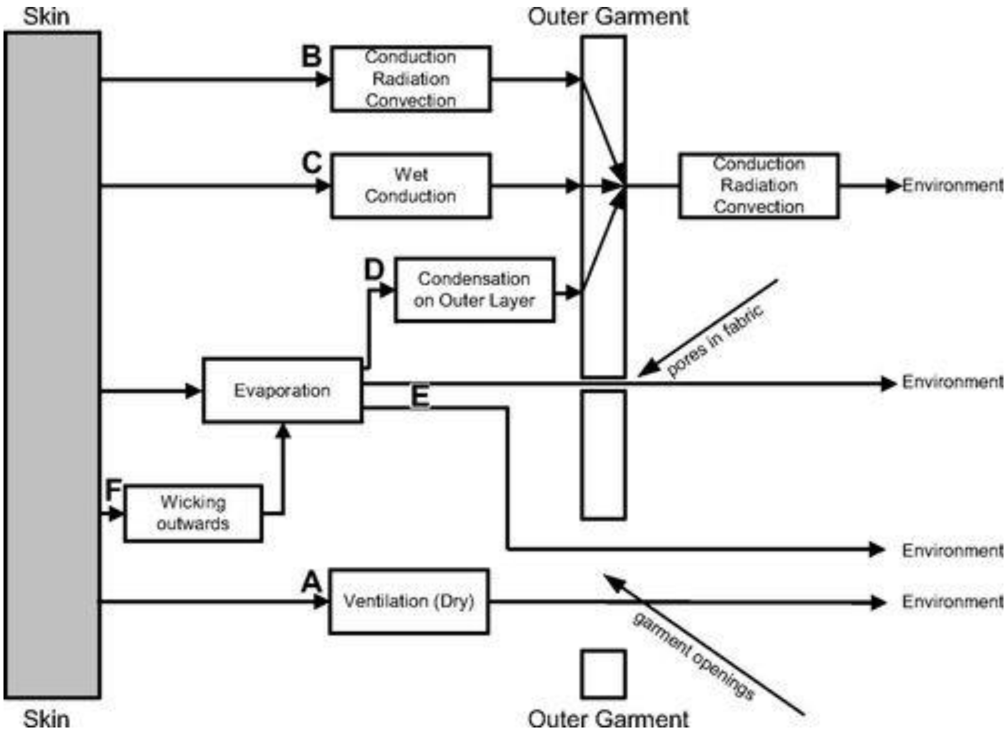


Figure 14. Schematic representation of heat transfer pathways through skin and clothing [125]

2.6.1.3 Effects of heat strain on cardiac output

When wearing heavy protective clothing, the human body tries to regulate a constant and comfortable core temperature. As a result, internal organs redirect blood circulation to the skin which needs an extra stroke volume by the heart that increases cardiac output [126]. The volume of blood the heart pumps through the circulatory system in a minute is known as cardiac output (CO) [126]. It is a vital indicator of how effectively the heart pumps nutrients and oxygen to the body's tissues. The following formula is commonly used for determining cardiac output, which is expressed in liters per minute (L/min):

Cardiac Output (CO)=Heart Rate (HR)×Stroke Volume (SV)

Where heart rate (HR) can be defined as the number of heartbeats per minute and stroke volume (SV) is the amount of blood pumped or ejected during ventricular contraction by the heart with each beat (measured in liters) [126]. Due to the increased load on the cardiovascular system, the body suffers from fatigue, dizziness, and even cardiovascular collapse [127]. Therefore, core temperature and cardiac output (heart rate) can be referred to as thermal sensation and physiological exertion respectively [90].

Firefighting is an activity that results in substantial cardiovascular and thermal strain [90]. Heat stress has been identified as a primary cause of cardiac events among firefighters, which have been responsible for 44% of all on-duty firefighter fatalities over the past decade [56]. Therefore, the Fire Service would undoubtedly benefit from reliable and useful measures of heat strain and the predictive assessment of the physiological effects of wearing ballistic PPE.

2.6.2 Physiological response to activity level

Studies have found that human physiological thermal strain increases with the increase of activity level in high temperatures [128] Activity level can be measured using MET value that quantifies energy expenditure relative to resting metabolism [129]. To calculate activity level, the metabolic equivalent is calculated using the Pandolf equation. The Pandolf Equation is a mathematical formula used in exercise physiology to estimate the metabolic energy expenditure (calories burned) during various physical activities. It takes into account different factors such as the individual's body weight, the efficiency of movement, and the intensity of the activity to estimate energy expenditure. Pandolf equation [130] is following:

$$M_w = 1.5W + 2(W+L)\,(L/W)^2 + \eta(W+L)\,[1.5V^2 + 0.35VG]$$

where, M_w= metabolic rate (watt); W= nude body weight (kg); L= clothing and equipment weight (kg); η= terrain factor; V= walking velocity (ms^{-1}); G= grade (%)

According to Pandolf [130], there are four components of the equation. A metabolic cost is proportional to the weight (M_1) calculated as 1.5 watts per body and is calculated as 1.5 watts per kg of body weight ($M_1 = 1.5W$). A metabolic cost of load bearing while standing (M_2) is affected by the total weight (subject + load) and is fitted as a function of the load to weight ratio squared ($M2 = 2.0 (W + L) (L/W)^2$. A metabolic cost for walking on the level (M_3) is related to a specific terrain (η), considered total weight moved and is a function of the speed squared ($M3 = \eta (W+L) (1.5 V^2)$. A metabolic cost for climbing grade (M_4) considers a specific terrain (η) and total weight $\eta (W+L) (0.35VG)$. However, this component needs further validation at speeds less than 0.7 ms^{-1}. equation is not used). The first section of the Pandolf Equation, i.e., [(M = 1.5W + 2.0(W + L) (L / W)2] assumes a 1.5 W/kg metabolic cost of standing without a load and accounts for additional load as a function of individual body weight. The second part of the Pandolf Equation, i.e., [$\eta (W + L) (1.5V^2 + 0.35VG)$], assumes a metabolic cost of walking on level grade (i.e., $\eta = 1$) is a function of the total weight of the individual and added velocity squared and accounts for percentage grade, velocity, total weight, and terrain.

According to Potter et al., (2013), Pandolf equation has a standing metabolic rate and a moving metabolic rate. When there is no motion, the second half of the equation is not used. The equation only provides an estimate of the metabolic cost of standing with or without a load is provided. The first section of the Pandolf Equation, i.e., [($M = 1.5W + 2.0(W + L) (L / W)^2$] estimates a 1.5 W/kg metabolic cost of standing without a load and accounts for additional load as a function of individual body weight. Load carriage is a core requirement of personnel serving in various physically demanding occupational settings, particularly firefighting [131]. These heavy loads with intense physical activities increase the activity level as well as the risk of hyperthermia, hypohydration, under-nutrition, and degraded mental and physical work capacities [114]. Mathematical algorithms that predict the metabolic cost of various physical activities are at the heart of occupational mission planning and safety assessment tools (e.g., establish work-rest cycles, water requirements, etc. [98]. The second half of the Pandolf Equation [η (W + L) (1.5V2 + 0.35VG)] takes into consideration the percentage grade, velocity, total weight, and terrain and assumes a metabolic cost of walking on level grade (i.e., η = 1) [132]. It is a function of the individual's total weight and added velocity squared. According to Fletcher et al., [133] and Natali, et al., [134] 1 MET (Metabolic equivalent) = 1.162 Watts/Kg

Therefore, Metabolic rate can be converted to Metabolic equivalent (MET) using the formula below:

$$MET = \frac{Metabolic\ rate\ (watts)}{Body\ weight\ (kg) x\ 1.162}$$

Human body responses differently in different activity level [128]. The physiological tolerance of activity level was investigated by Montain et al. [135] at various exercise intensities, where the metabolic rate varied from 425 W to 600 W. At ambient temperatures of 35 °C and 43 °C, they found that when seven male volunteers were recruited to perform heavy-intensity activities, the participants' rectal (core) temperatures and sweating rates increased significantly. Another study by Nag et al. [136] found that participants’ heart rate increased when performing high intensity tasks at where the corresponding metabolic rate ranged between 275 and 600 W, for 90 min at temperatures of 34.4-42.2 °C.

Although it is expected that high-intensity exercise in high temperature will raise core temperature and sweating rate, this study quantifies these increases for two specific temperature conditions (35°C and 43°C) and workloads. Establishing acceptable heat exposure thresholds and comprehending physiological limitations in extreme environments relies significantly on these data. For example, understanding the rate of increase of core temperature or the intensity-dependent change in sweating efficiency could assist with suggesting safety protocols (e.g., length of work/rest cycles or hydration demands) for the firefighters.

Table 1. Physiological responses to heat strain

Authors	**Temperature & RH**	**Activity level**	**Exposure time**	**Findings**
Tian et al. (2021)	26°C, 30°C, 33°C and 37°C RH 70% (0.1 m/s ws)	Light to moderate	85 minutes (each exp)	Core temperature (T_c) ↑ Skin temperature (T_{sk})↑ Heart rate (HR) ↑ **No changes**
Fan et al., (2018)	26°C, 30°C, 33°C and 37°C ; RH 70%, 88-90%	Light (Sitting in an office setting at doing light work at desk)	175 minutes	T_{sk}↑ T_c↑
Shi et al. (2013)	32, 36, and 40 °C RH 40,60,90%	Light-Moderate-Heavy	80 minutes	T_c↑ HR↑
Nag et al., (2007)	34.4–42.2 °C	Light-Moderate-Heavy	55 minutes	T_{sk}↑ T_c↑
Montain et al., (1994)	35°and 43°C RH 50% and 20%	Heavy (180 mins treadmill walks)	180 minutes	T_c↑ HR↑
Gagge et al. (1967)	10°C, 20°C, and 30 °C RH 40%	Light-Moderate-Heavy (pedalling a bicycle ergometer)	70 minutes	Thermal sensation was observed. But no significant changes in T_c and T_{sk}

Different activity level was incorporated by Shi et al. [137]the physiological parameters of five male participants. The parameters were assessed during sitting and walking (3.5 and 5.5 km/h) at air temperatures of 32, 36, and 40 °C. The study found that the rectal temperature, sweat rate, and heart rate during walking were always higher than when sitting. On the other hand, Gagge et al. [138] found that when air temperature ranged from 10 °C to 30 °C, there were variations in thermal perception and physiological reactions at various activity levels. They observed that skin temperature and ambient temperature were associated with thermal sensation, but thermal sensation was not associated with metabolic rate, muscle temperature, or core temperature. Important insights into human thermoregulation and thermal perception are illustrated by the findings from Shi et al. and Gagge et al. Understanding how physical exertion affects heat strain requires an understanding of how increased activity levels (walking vs. sitting) in hot conditions increase physiological strain, such as core temperature, sweating, and heart rate, which Shi et al.'s findings validates. However, Gagge et al.'s study shows that skin temperature and ambient temperature have a greater impact on thermal sensation than physiological factors, such as metabolic or core temperatures. It suggests that perceptions of comfort in moderate conditions (10°C to 30°C) are influenced more by the outside temperature than by physiological indicators of heat strain.

2.6.3 Differences in physiological responses between male and female

Historically, the profession of combating fires has been dominated by men. Over the past decade the number of female firefighters has increased. According to NFPA (2022) [139], there are approximately 90,000 female firefighters in the country equating to 9% of all firefighters. However, there is a lack of studies pertinent to female firefighters and their physiological responses to heat strain compared to male firefighters while wearing ballistic vests with turnout gear.

Women typically have a larger ratio of body surface to body mass, a higher content of subcutaneous adipose tissue, a lower exercise capacity, and a lower blood volume. These differences in physical characteristics cause women to respond differently than men to endogenous heat production (through internal or metabolic activity) during exercise as well as to exogenous heat production (through external heat exposure) and total heat loss [140]. The main characteristics of female physiology (e.g., sex hormones, body fluid homeostasis, exercise capacity, etc.) which differentiate thermoregulation between men and women are body composition (e.g., muscle and body fat content), anthropometric attributes (e.g., body mass and size), and social behavior (e.g., daily physical activity) [141]. There are several studies (Table 2) identifying differences in physiological responses (core temperature, mean skin temperature, and cardiac output) studies between males and female.

Table 2. Differences in physiological responses to heat strain between males and females

Authors	**Ambient**	**Activity level**	**Exposure time**	**Clothing**	**Findings**
Renberg et al. (2022)	40°C RH 15%	Light –Moderate -Heavy	60 minutes	Firefighting turnout suit with gloves, boots and SCBA	Increases in T_{re}, T_{sk}, and HR were observed throughout the exposure for all participants, but no differences between males and females
Anderson et al., (2022)	32.5 ◦C RH 55%	Moderate -Heavy		Military uniform	Body core temperature elevation was similar between males and females during the first heavy work bout, then was significantly lower in females for the remainder of the trial

Table 3. (continued)

Authors	**Ambient**	**Activity level**	**Exposure time**	**Clothing**	**Findings**
Chudecka et al., (2015)	25°C RH 60%		20 minutes	Underwear	The results showed that T_{sk} was significantly higher in women than in men in chest area. T_{sk} were similar for women and men in hand areas. In the other part of the body surface areas, T_{sk} were significantly lower in women than men.
Lan et al;, (2008)	18 to 32°C		60 minutes	Long sleeved shirt and long trousers	Males have significantly higher HR than females. Female mean skin temperatures are lower than male mean skin temperature at different temperature.
Wyndham et al;, (1965)	32 to 35°C,	Moderate	4 hours	Underwear	T_{re} and HR increased more rapidly in females than males.

Renberg [84] indicated that there were no significant differences in core temperature between male and female. In a study by Anderson [142], body core temperature elevation was similar between males and females during the first heavy work bout, then remained significantly lower in females for the rest of the trial. Studies found that mean skin temperature was significantly lower in women than men except for chest areas [140] [143]. However, no differences in core temperature, mean skin temperature, and heart rate were found between males and females in a study by Renberg [84].

(a) Rectal temperature (T_{re}) and (b) change in rectal temperature (ΔT_{re}) for female and male participants [84].

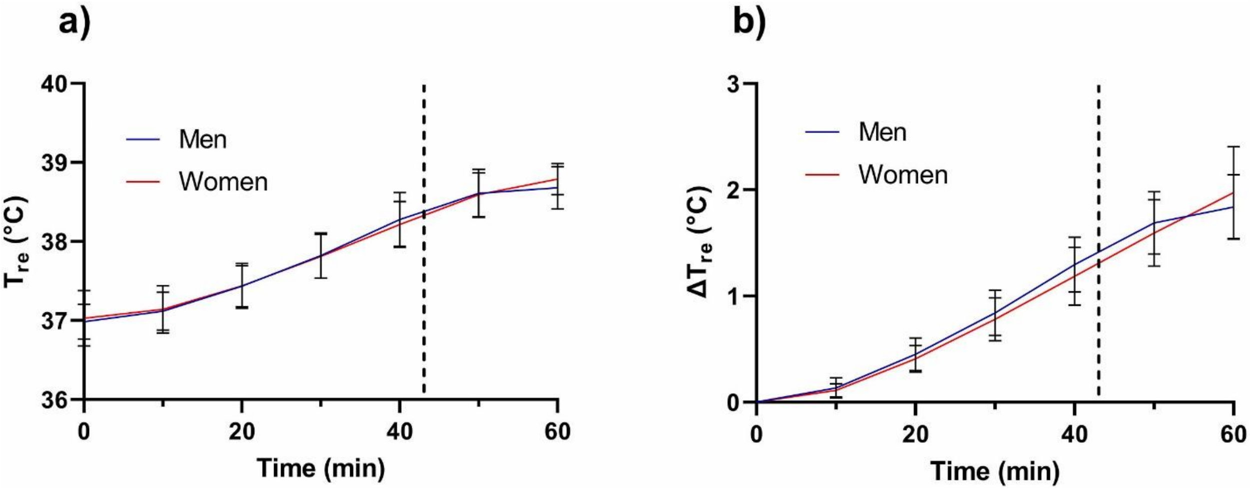
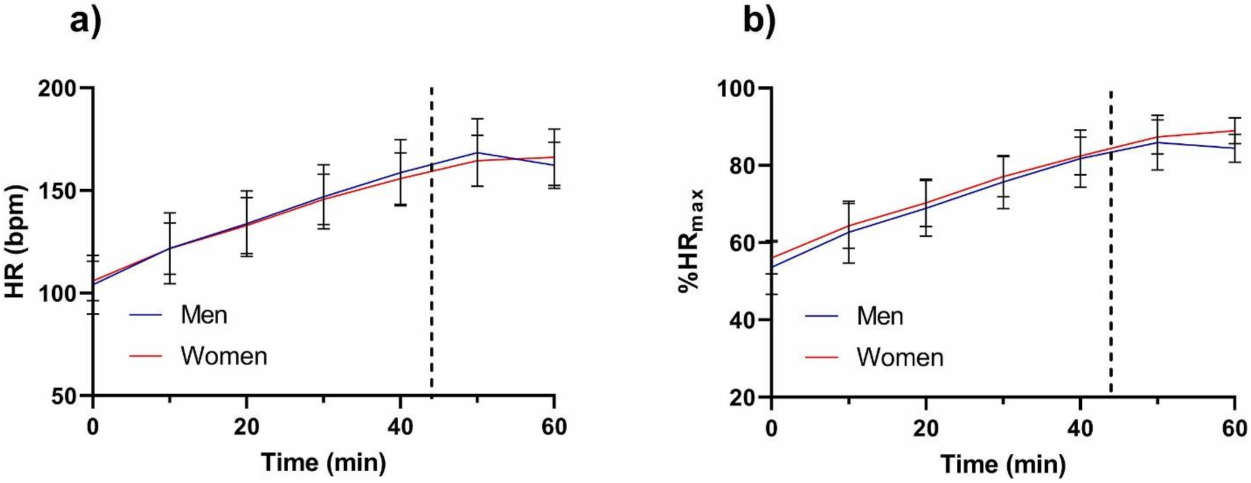


Figure 15. (a) Rectal temperature (Tre) and (b) change in rectal temperature (ΔTre) for female and male participants[84].



(a) (b)

Figure 16. (a) Mean heart rate (HR) (a) and percentage of maximal HR (%HRmax) (b) for female and male participants [84]

Chudecka et al. (2015) and Lan et al. (2008) found that core temperature and heart rate were lower in female than male [143]. In contrast, a study by McLellan (1998) compared the thermoregulatory responses of men and women wearing firefighter PPE (semipermeable NBC protective overgarment, impermeable boots and gloves, and a C4 respirator with underwear or jogging shorts, cotton/polyester T-shirt or sports bra, socks, jogging shoes, a cotton and polyester blend combat jacket and trousers) while intermittently walking at 1.1 ms^{-1} at 40 °C and reported shorter tolerance times for the women and higher T_{re}, and HR for the women throughout the trial [144] due to their lower sweat rate and fitness level and higher fat distribution in the body. Another study by Shapiro et al. (1980) found that in hot humid condition ((35–37°C, 80–90% RH) core temperature, mean skin temperature and heart rate was lower in females than males. However, in hot/dry (49–54°C, 10–20% RH) condition, core temperature, mean skin temperature and heart rate was higher in females than males. They concluded that males are more efficient in sweating evaporation in hot dry condition than females. The contradictory results demonstrate the complexity of gender-based physiological responses and the need for further research to fully comprehend these differences.

2.6.4 Thermal modeling for physiological responses

2.6.4.1 TAITherm Model

TAITherm is based on Fiala model that was used to simulate transient heat transfer through the body, clothing, and environmental system during firefighting activities. By incorporating experimentally measured thermal insulation (R_t) and evaporative resistance (R_{et}) values from the Newton (male) and Liz (female) manikins, the model calculated predicted core temperature, mean skin temperature, and cardiac output under defined metabolic workloads (2.8–3.5 MET) and environmental conditions (30-35°C, 30-50% RH). The coupling of empirical data with computational modeling provides a physiologically realistic framework for assessing heat strain, gender-specific thermal responses, and PPE performance optimization bridging laboratory testing with predictive human thermophysiology.

The Fiala model is a comprehensive, multi-node human thermoregulation model that predicts core and skin temperatures, sweating, shivering, and blood flow regulation in response to environmental and clothing conditions. It represents the body as a system of interconnected thermal and moisture nodes, each governed by the principles of heat and mass transfer.

The human body is divided into several concentric layers: bone, muscle, fat, skin, and clothing and each represented by a series of thermal nodes (pink circles) connected by thermal resistances. Bone and muscle layers act as inner core heat sources due to metabolic activity. Fat provides insulation and moderates heat flux toward the skin. Skin and clothing layers serve as the primary interfaces for heat and moisture exchange with the environment.

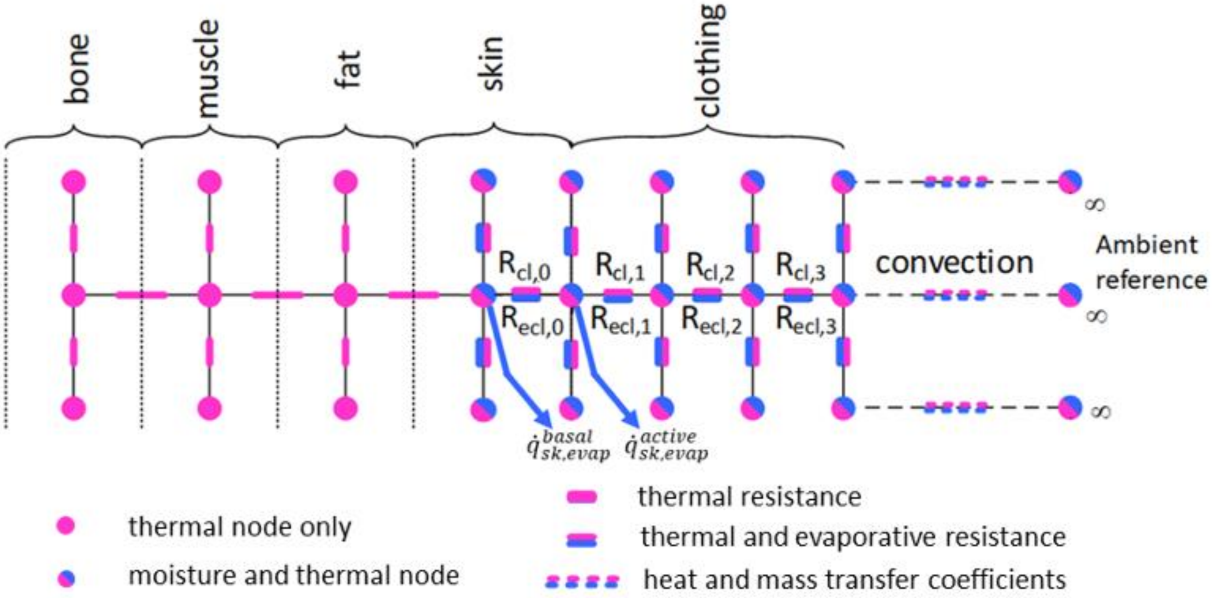


Figure 17. A schematic of the nodal network used by the TAITherm[145]

Each vertical column in the model represents a one-dimensional heat transfer pathway through these layers, while the horizontal connections represent blood perfusion and metabolic heat exchange between adjacent tissues. The Fiala model integrates a physiological control system that modulates blood flow, shivering, and sweating based on deviations from the body’s temperature setpoints. Vasodilation increases blood flow to the skin when the core overheats, enhancing convective heat loss. Vasoconstriction restricts blood flow when cold, preserving core temperature. Sweating is activated through active evaporation, allowing latent heat removal. Shivering increases metabolic heat generation when core temperature drops. This feedback control links the thermal state of the body (inputs) with physiological responses (outputs), allowing transient prediction of body temperature under changing environments, workloads, and clothing conditions.

2.6.4.2 JOS-3 Model

The JOS-3 thermoregulation model is derived from the multi-segment human thermal model developed by Fiala, but it employs a reduced number of body segments and a simplified mathematical framework. It represents a direct evolution of Tanabe’s 65-node model [146]. Relative to the original 65-node formulation, JOS-3 decreases the number of concentric tissue layers (e.g., fat and muscle) in several body regions by integrating them into either the core or skin nodes, while simultaneously introducing explicit arterial and venous compartments.

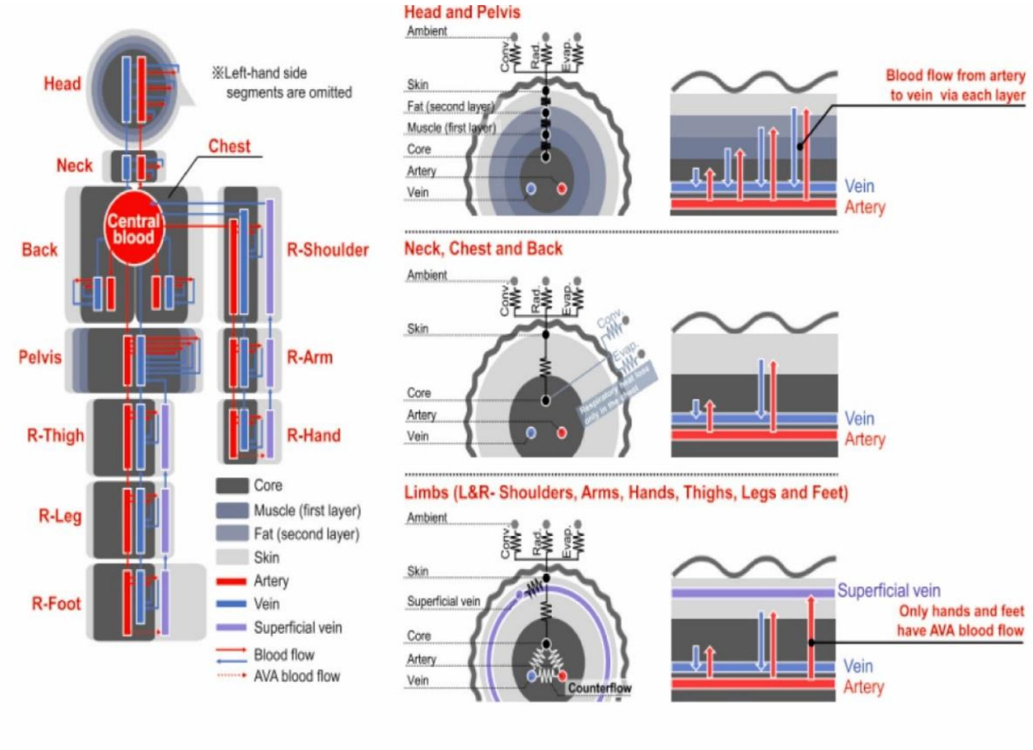


Figure 18. JOS-3 nodes and heat exchange mechanism[146]

A key advancement of JOS-3 is its enhanced representation of blood circulation, incorporating interconnected artery and vein nodes within each body segment, as well as superficial veins in the extremities. The spatial distribution of arterial and venous blood flow across body parts follows the formulation proposed by Smith [146]. In addition, JOS-3 explicitly models arteriovenous anastomoses (AVA) in the hands and feet, enabling improved prediction of peripheral heat exchange and overall thermophysiological responses. Figure 18 illustrates the body segmentation, node structure, and heat transfer pathways incorporated in the JOS-3 model.

2.6.4.3 USAREIM Model

The USARIEM framework consists of three empirical regression models developed to predict final equilibrium rectal temperature (T_{ref}), heart rate (HR), and sweating rate (m_{sw}) across varying combinations of walking-induced metabolic workload, environmental heat stress, and clothing conditions [147]. The predictive equations for T_{ref} and HR were originally reported by Givoni and Goldman [148], while the sweating-rate model was later introduced by Shapiro et al. (1982).

The regression formulation for T_{ref} is based on the fundamental assumption that, for any given combination of metabolic heat production, environmental heat load, and clothing insulation, a hypothetical steady-state balance of core and skin temperatures exists in which metabolic heat can be dissipated at the same rate it is produced. The general form of the predictive equation for T_{ref} is expressed as:

$$T_{\mathrm{mf}} = T_0 + a(M_{\mathrm{net}}) + b\mathrm{H}(\mathrm{r} + \mathrm{c}) \ + c\exp\left[d(E_{\mathrm{req}} - E_{\mathrm{max}})\right]$$

where T_0 represents the initial rectal temperature; M_{net} and H_{r+c} denote the metabolic and environmental heat loads, respectively; and (E_{req} - E_{max}) represents the difference between the evaporative heat loss required for thermal equilibrium and the maximum evaporative capacity of the environment (W/m^2). The coefficients a,b,c and d are empirically derived from regression analysis of an experimental database.

Once determined, T_{ref} is used to model the temporal progression of rectal temperature. In this formulation, mean skin temperature (T_{sk}) is treated as a fixed independent variable, typically set at 36 °C. The skin surface is assumed to be fully wet, and the water vapor pressure at the skin surface is held constant at 44 torr [147]. (1 torr ≈1 mmHg ≈133.3 Pa)

2.6.4.4 FAME Lab (PHS)

The FAME Lab Predicted Heat Strain software (PHSFL) is a freely available offline tool designed to calculate Predicted Heat Strain (PHS) for groups of individuals in accordance with ISO 7933:2018 [149]. Since its introduction, PHSFL has been applied across a wide range of occupational environments, where it has provided meaningful insight into the physiological consequences of heat stress in working populations. The tool is also currently used by the military forces of the North Atlantic Treaty Organization, where it delivers accurate, real-time guidance for managing heat strain under operational conditions. Built upon the original ISO Predicted Heat Strain (PHS) computational framework, the software was developed to address two key limitations of the standard formulation. First, it explicitly incorporates mechanical efficiency which is defined as the proportion of metabolic energy converted into external mechanical work which is treated as negligible in the original ISO PHS model. Second, it enables the simulation of multiple consecutive exposure periods within a single scenario, allowing environmental, workload, and clothing conditions to be modified over time. To enhance usability and better support physiologists, industrial hygienists, and occupational physicians, the PHSFL platform provides streamlined functionality for calculating a wide range of environmental and physiological parameters with minimal user input [149] .

In addition to the offline version, a web-based implementation of PHSFL has been developed using HTML, CSS, and JavaScript for browser-based accessibility. The backend architecture, which incorporates the core PHSFL computational model, was implemented in PHP and is founded on a modified version of the ISO 7933 standard previously published by the developers. This codebase has been further updated to reflect revisions introduced in the 2023 edition of ISO 7933. The online version of PHSFL is freely accessible via https://habitatscience.org/ and is designed for cross-platform use, supporting laptops, desktop computers, and mobile devices across multiple operating systems, including Windows, Unix, macOS, iOS, and Android [149].

2.7 Research Gaps and research questions

There is a lack of published after-action reports regarding the implementation of firefighter teams within a tactical, law enforcement environment. Although there is a substantial amount of research on heat strain caused by ballistic vests in military or law enforcement settings and by firefighter gear in firefighting contexts, few studies analyze the combined effects of wearing ballistic vests and firefighter gear simultaneously. Detailed physiological responses, such as core temperature, mean skin temperature, and sweat rate, specific to the combination of ballistic vests and firefighter gear, are still underexplored. Comprehensive studies measuring these parameters under realistic conditions are needed.

According to ASTM E3348 [9], firefighters should not wear ballistic vests with turnout gear. However, it neither provides an appropriate guideline with possible solutions nor suggests a combination of clothing ensembles. Also, the standard suggests wearing ballistic vests underneath the turnout gear which is self-contradictory. On the other hand, a survey study [83]showed that most firefighters wear ballistic vests over the turnout suit and some firefighters wear the vest under turnout suit. Additionally, the standard also encourages determining whether the added ballistic protection from ballistic vests when worn with turnout gear has a detrimental effect on heat stress. Therefore, it is crucial to assess the changes in thermal strain caused by ballistic PPE in combination with firefighter PPE and develop guidance for FD (chiefs, managers) to support decision making on the physiological impact of using ballistic PPE in operational context.

Based on the gap in the standards and lack of existing scientific studies on the thermal effect of wearing firefighting turnout gear with ballistic vests, our study proposes several combinations of ensembles and aims to test them scientifically under standard environmental conditions.

The literature review and research gaps lead to the following research questions to satisfy Objective 1 and Objective 2:

Research question 1: How much heat strain does the ballistic vest cause to the firefighters while wearing it along with turnout gear in realistic conditions?

Research question 2: Which properties of the ballistic vest (weight, and threat level) have the largest physiological impact on the body?

Research question 3: Can the factors causing any of the predicted differences in physiological responses between males and females while wearing different ballistic-wear configurations in firefighting be explained in terms of previously known differences in male and female response to heat stress?

Research question 4: How can thermal virtual modeling be used as a tool to support firefighters to make decisions about the use of ballistic vests and their effects of heat strain?

Research Objectives

The study we propose has two objectives. The objectives of our study are:

Objective 1: Understanding the effects of wearing ballistic vests in conjunction with turnout gear on heat transfer in standard environmental conditions. Specific tasks include:

Task 1: Identifying and establishing controls and variables of firefighter clothing ensembles for experimental design

Task 2: Assessing the thermal resistance and evaporative resistance properties of the ballistic vest in comparison to standard turnout gear

Objective 2: Understanding differences in physiological responses to wearing ballistic vests in conjunction with turnout gear between males and females. Specific tasks include:

Task 3. Exploring how the load, duration, and intensity of firefighting activities impact heat strain in males and females wearing the combined gear

Task 4. Comparing physiological responses between males and females using simulation data while wearing while wearing ballistic vests with firefighting gear

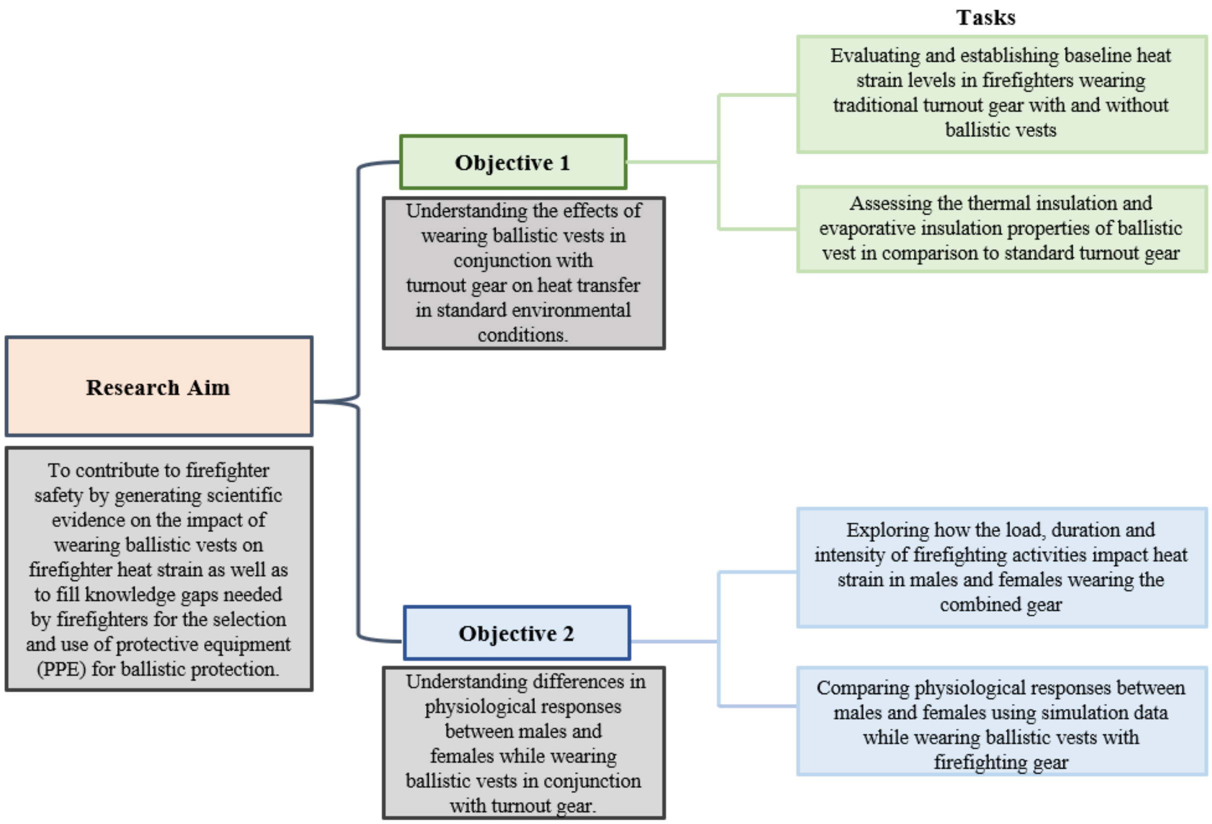


Figure 19. Schematic of research approach

CHAPTER 3

PUBLISHED WORK

Mica, M., Mathews, M., Barker, R., Deaton, A., & DenHartog, E. (2025). Survey of Firefighters' usage of Ballistic Vests in North America. Journal of Textile and Apparel, Technology and Management, 13(1). *[Formatted as published]*

This chapter presents the results of a survey conducted on the current use of ballistic vests by firefighters and Emergency Medical Services (EMS) personnel in North America [83]. The survey results provide information on the types of ballistic vests typically worn, deployment practices, levels of ballistic protection and training practices for firefighters. This chapter describes how ballistic vests are worn with turnout gear and identifies the need to consider the effects of wearing ballistic vests on heat strain, interoperability of firefighter gear, as well as potential flammability issues and exposures to thermal threats from flammable materials.

Survey of firefighters' usage of ballistic vests in North America

Mushfika Mica[a*], Marc Mathews[b], Roger Barker[c], Anthoney Deaton[d], and Emiel DenHartog[e]
[a,b,c,d,e] Textile Protection and Comfort Center,
Wilson College of Textiles,
Raleigh, NC USA

ABSTRACT

Reports of bullet injuries to firefighters and emergency medical technicians (EMTs) are often found in media reports and firefighter periodicals. There are also several incidents where firefighters were shot and killed in emergency situations (e.g. domestic violence, civil unrest,

active shooter scenarios, etc.) that don't include fire. First responders must, therefore, be appropriately equipped with ballistic vests to execute multidisciplinary missions that go against the single-discipline paradigms. This paper presents the results of a survey conducted on the current use of ballistic vests by firefighters and Emergency Medical Services (EMS) personnel in North America. The survey results provide information on the types of ballistic vests typically worn, deployment practices, levels of ballistic protection and training practices for firefighters. This paper describes how ballistic vests are worn with turnout gear and identifies the need to consider the effects of wearing ballistic vests on heat strain, interoperability of firefighter gear, as well as potential flammability issues and exposures to thermal threats from flammable materials.

3.1: Introduction

The growing number of tragic deaths from firearms injuries leaves little doubt that firefighters and EMS personnel need ballistic protection in many emergency response scenarios [150]. Federal agencies have recognized the need for ballistic protection for firefighters and EMS responders [151]. As part of a research report conducted by the Federal Emergency Management Agency (FEMA) on Mitigation of Occupational Violence to Firefighters and EMS Responders, National Institute for Occupational Safety and Health (NIOSH) recommended that firefighters should be provided ballistic vests or bullet-resistant personal protective equipment (PPE) to train on, and consistently enforce its use when responding to potentially violent situations [152]. Department of Homeland Security (DHS) endorses such acquisitions and provides funds through the Assistance to Firefighters Grants Program (AFG) program to fire services to purchase ballistic protective equipment. Many fire departments require that ballistic-resistant vests be worn on emergency calls. These departments need more guidance and information to help their selection and use of ballistic PPE in emergency response. Ballistic vests can add more than forty pounds of weight to the firefighter, besides adding bulk, stiffness, and ergonomic encumbrance. The discrepancy between the heat resistance requirements of turnout suits certified to the National Fire Protection Association (NFPA) 1971 standard and the lack of flammability and heat-resistant requirements for ballistic vests is also apparent [153]. This is an important safety consideration if firefighters wear ballistic vests with turnout suits while performing limited fire suppression activities in hostile environments, including suppressing fires generated by burning cars and dumpster fires. Some materials used in ballistic vest construction, particularly materials made from polyester and nylon fibers in ballistic plate carriers, burn and melt in heat and flames. This paper discusses the findings of a survey of firefighters and EMS personnel who wear ballistic vests in emergency response. It identifies a need for a better understanding of performance trade-offs associated with firefighter selection and use of ballistic vests.

3.2: Methodology

We surveyed 300 firefighters to acquire information about their use of ballistic vests in phases of firefighting response and active shooting scenarios. Also, we had a discussion meeting with a manufacturer of firefighter ballistic vests. Our goal was to obtain a better understanding of the factors contributing to the selection of ballistic vests in firefighter operational response scenarios, including the use of turnout gear. We formulated questions in SurveyMonkey. The research survey was reviewed and approved by the North Carolina State University Institutional Review Board (IRB) on May 10, 2023, as exempt from the policy as outlined in the Code of Federal Regulations (Exempt d.2). The NC State University IRB complies with requirements found in

Title 45 part 46 of The Code of Federal Regulations. The survey link was sent to different fire departments across the USA and 300 firefighters responded to it. We also emailed a few manufacturers of ballistic vests for firefighters and one manufacturer responded to it.

We surveyed firefighters in North America, primarily located in the United States. Responses may be different for firefighters located in parts of the world that conduct firefighting operations in different climates ranges, use different firefighting tactics or wear gear certified to performance standards other than the NFPA 1971 Standard for Structural Firefighter PPE. The findings of this study do not represent specific response scenarios or conditions. Every fire scene is unique and presents different risks to firefighter safety. Therefore, this study does not attempt to recommend any particular operational tactics, gear selection, job assignment or rehabilitation routine. These are decisions best made by professional firefighters on the scene.

3.3: Results

3.3.1: Geographic Locations

Using the Survey Monkey™ platform, we surveyed firefighters from different geographical regions of the country representing different climate zones (Figure 1a). Most of the firefighters surveyed were from the South Atlantic (40%), Mountains (20%), and Middle Atlantic (10%) regions of the United States. Responses came from urban, suburban, and rural areas (Figure 1b).

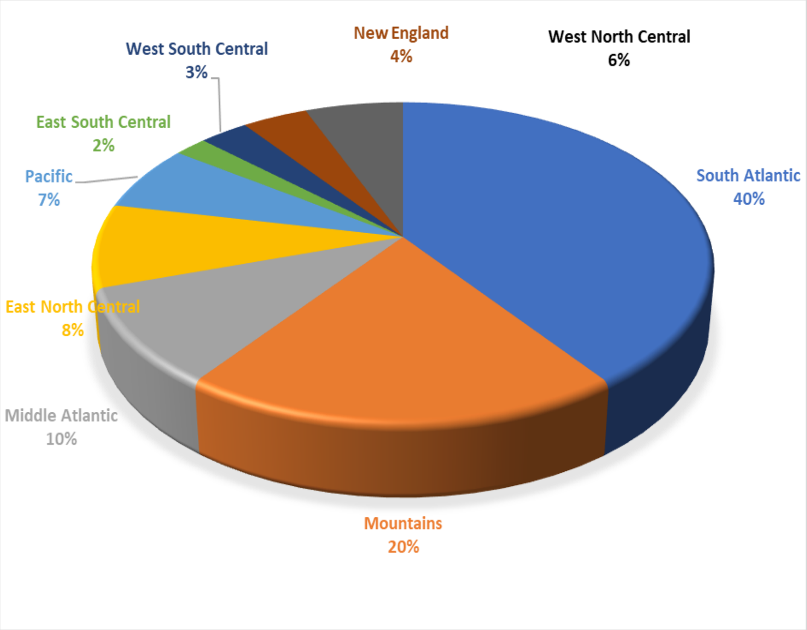


Figure 1a. Geographic location of the firefighters surveyed

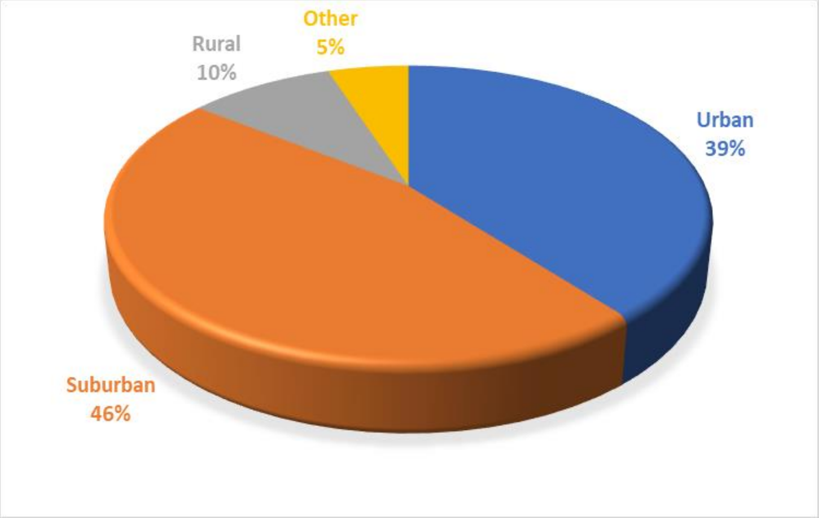


Figure 1b. Regional distribution of surveyed responders

3.3.2: Distribution by rank and firefighter

Firefighters who responded to the survey held different ranks and had different years of service. Most were career firefighters; however, many were volunteer firefighters, or they worked in departments made up of both career and volunteer firefighters (Figure 2a). They held various ranks and performed different jobs in the fire department (Figure 2b). Most had significant experience as firefighters. Their average service time exceeded 5 years, with many having more than 20 years of experience as firefighters and emergency responders (Figure 2c).

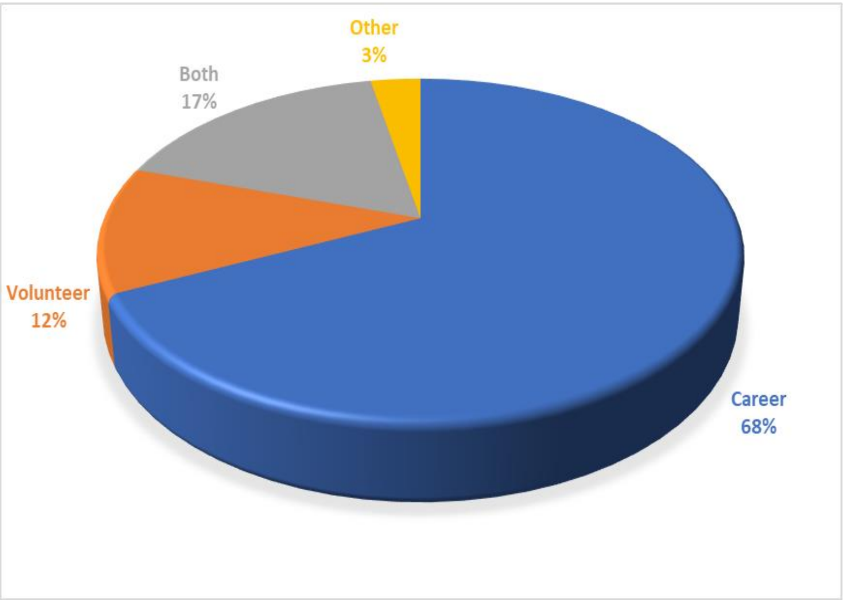


Figure 2a. Distribution of career and volunteer firefighters participating in the survey

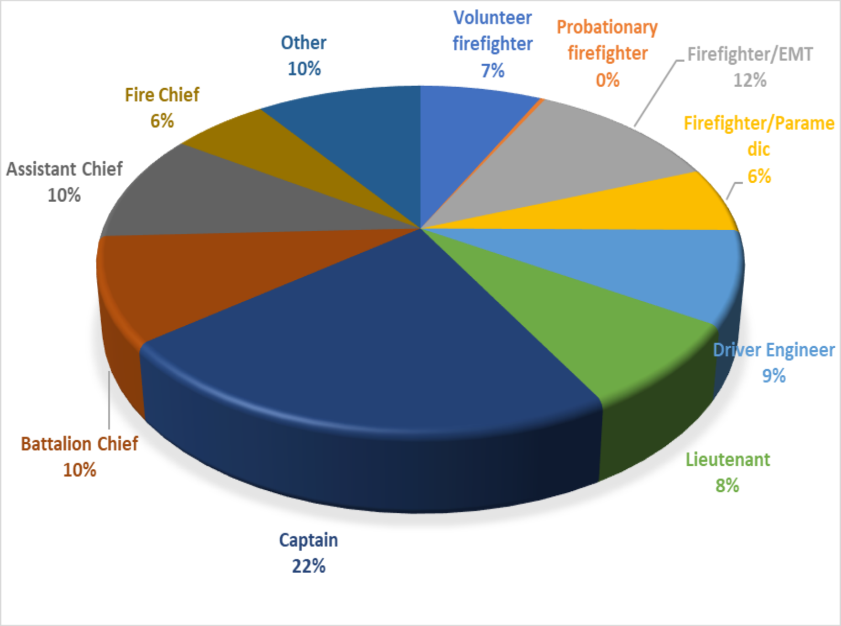


Figure 2b. Rank of firefighters participating in survey

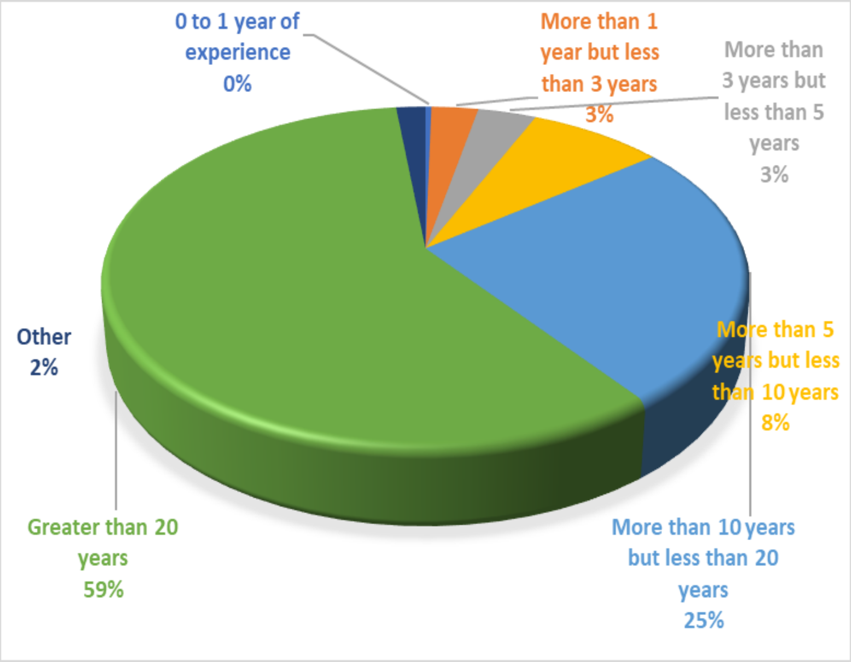


Figure 2c. Years of experience of firefighters participating in the survey

3.3.3: Firefighter use of ballistic gear

Our survey found that most (78%) responding firefighters have access to ballistic protective equipment. Figure 3 showed the most commonly deployed items of ballistic gear including ballistic protective helmets, soft ballistic vests, and side and back armor planes.

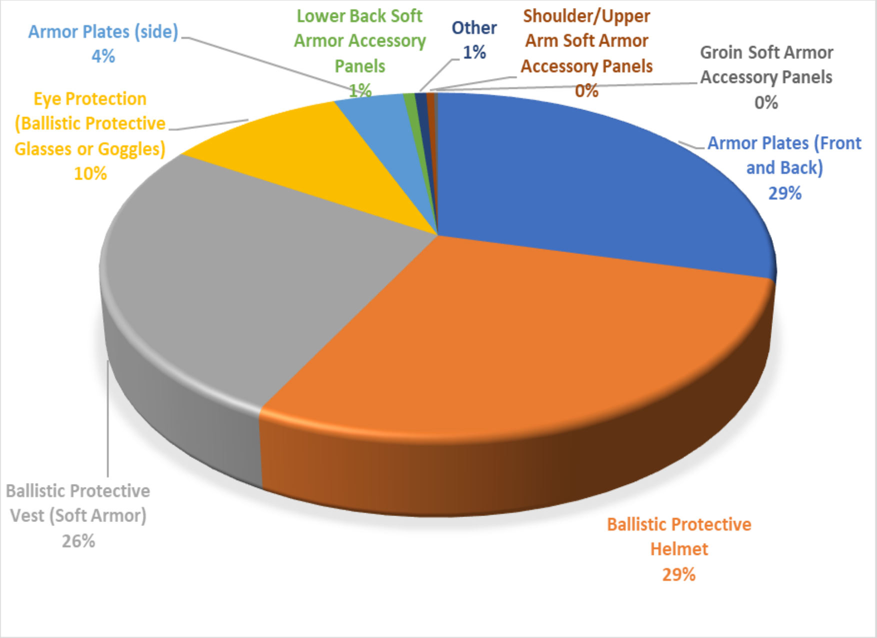


Figure 3. Ballistic protection worn by firefighters

Firefighters typically wear ballistic vests over a station uniform without turnout gear (51%). They wear ballistic vests with ballistic helmets, ballistic eyewear (12%), and ballistic vests worn under turnout jackets (2%). It is important to understand the reasons for this choice to reduce the barriers to the use of ballistic gear.

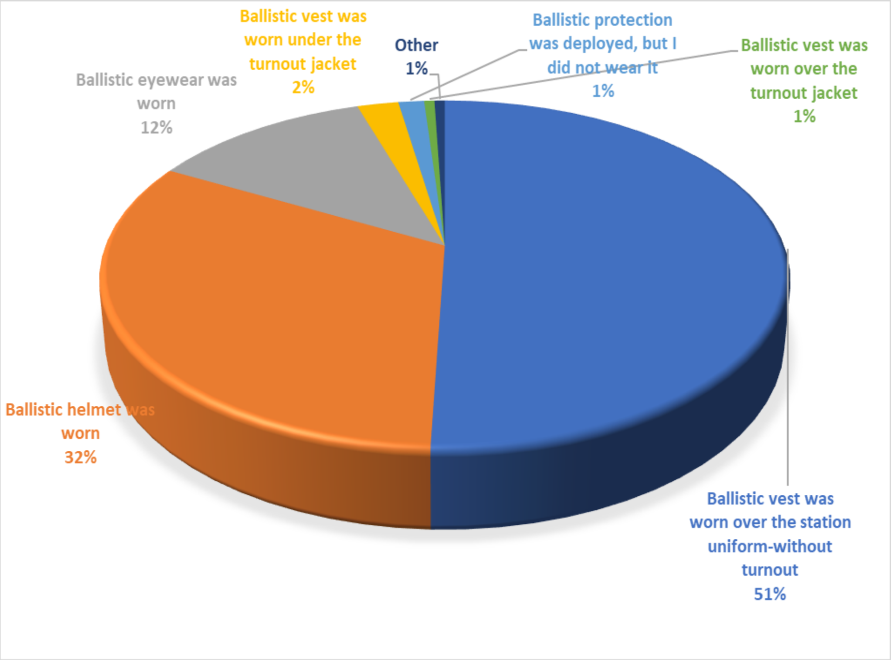


Figure 4. Configurations firefighters wear with the ballistic protective vest

3.3.4: Ballistic vest issuance and training:

According to survey results, 69% of ballistic protective equipment is a shared resource whereas 12 % of ballistic equipment is issued individually (Figure 5).

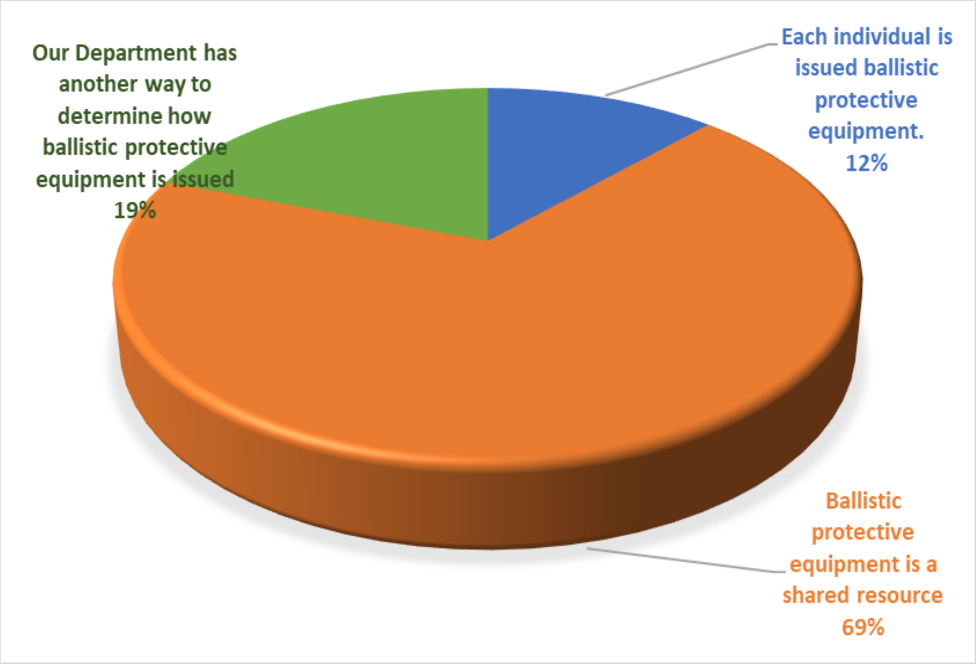


Figure 5. Issuance of ballistic equipment individual or shared

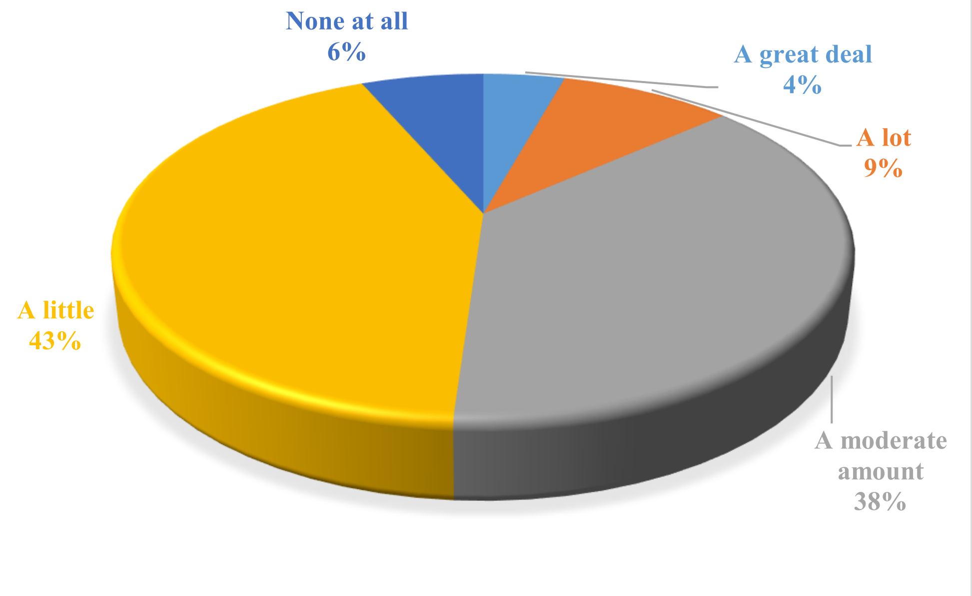


Figure 6. Training on equipment

Survey results showed that only 4% of firefighters received a great deal of training, while 43% received little, and 6% received no training.

The survey also showed the scenarios where the firefighters received ballistic protective equipment training, such as active shooter (54%), civil unrest (25%), and EMS (17%) (Figure 7). This indicates that firefighters are being prepared for high-risk and potentially dangerous situations where they need ballistic protection.

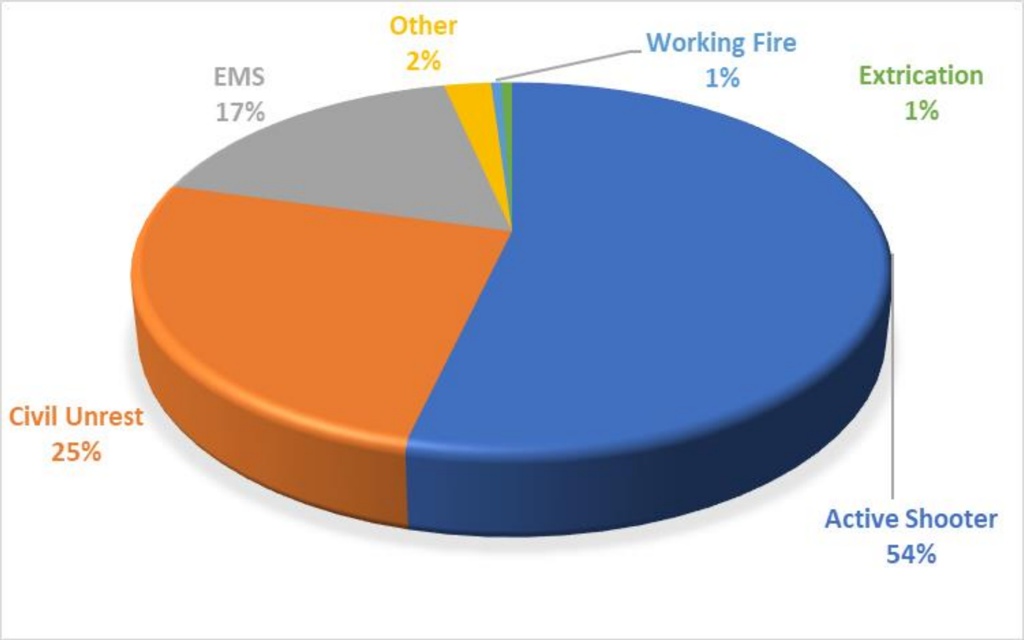
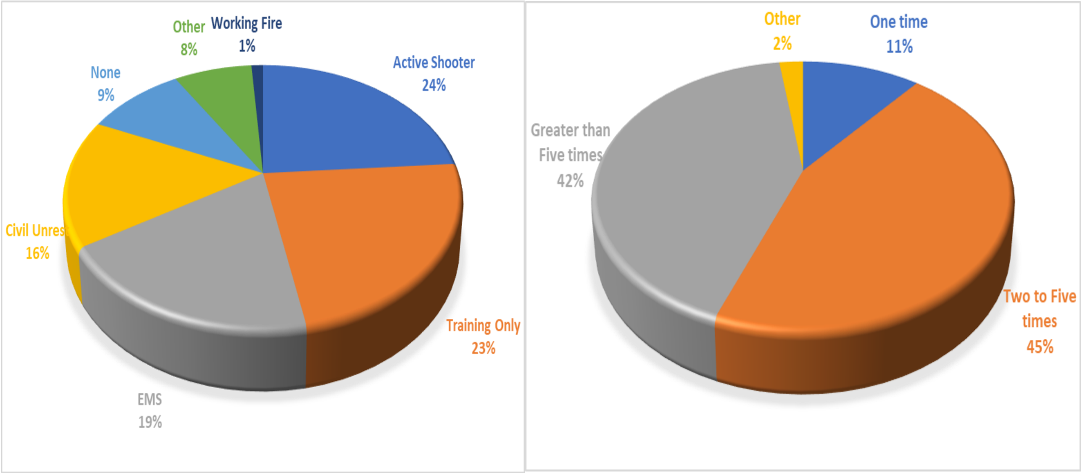


Figure 7. Emergency response where scenarios firefighters received ballistic protective equipment training

3.3.5: Scenarios encountered by firefighters where ballistic protection is deployed

The deployment scenarios where firefighters use ballistic protective equipment include active shooter (24%), EMS (19%), and training (23%) (Figure 8). Nine percent of firefighters had never worn ballistic protective equipment.



(a) (b)

Figure 8. Scenario where firefighters have personally worn ballistic protective equipment (a) & Frequency of firefighters' use of ballistic protective equipment (b)

Our survey shows that 45% of firefighters have worn ballistic protective equipment two to five times over the course of their service (Figure 8b). Some have worn ballistic gear more frequently, while others may wear it only once in their career as a firefighter.

3.3.6 Discussion of firefighters' ballistic vests with a manufacturer

Researchers reached out to several manufacturers via email and had a discussion with a manufacturer of ballistic vests for firefighters. Although the researcher was able to meet with only one manufacturer, the discussion was very informative. Therefore, the discussion was included in the results section.

Table 1 showed a summary of the information gathered from the manufacturer that markets ballistic PPE to firefighters. It provides a better understanding of the factors that influence their selection of ballistic vests by fire departments.

Table 1. Content analysis: Factors that influence firefighters' selection of ballistic vests

Theme	Subtheme
Top priority considerations	Wearability with turnout gear
	Interoperability with SCBA and helmet
	Low budget
	Maximum protection
Ballistic vest features for firefighters	One size fit all/ adjustable
	Not flame resistant
	NIJ certified
Law enforcement (LE) vs firefighter (FF) ballistic vests	LE have very specific and different movements than FF which leads to different cuts of ballistic vests
	Rectangle neckline and armhole for FF whereas round for LE
	Not best fit but easy to make panels for FF because of straight cut
Issues	Costly
	Bulky
	Less Mobility
	One size fits all causes fir problem
Common vest configurations	Soft armor
	NIJ Level IIIA (*handgun-9mm ammunition)*
	Extra front and back plates/panels for rifle protection
	Side panels are stab resistant
Current gaps in FF ballistic vests that should improve	Should be an everyday wear vest
	Should be lighter in weight
	Should provide custom fit or at least two sizes (from size Small-Medium and Large- Extra Large) vests

Firefighters' top priorities when selecting ballistic vests include cost, maximum protection, compatibility with SCBAs and helmets, and wearability with turnout gear. The ballistic vests are not usually flame resistant but are usually adjustable, one-size-fits-all, and NIJ-certified. Firefighter ballistic vests, in contrast to law enforcement vests, feature rectangular necklines and armholes for improved mobility; nonetheless, the straight-cut design facilitates panel manufacture but does not offer the best fit. High cost, bulkiness, decreased mobility, and fit problems imposed upon by the "one size fits all" are some of the main obstacles. Ballistic vests for firefighters should be made lighter, more wearable, and offered in at least two sizes (S-M and L-XL) for a better fit.

3.4: Discussion

Figure 5 indicated that most fire departments share ballistic protective equipment, typically one size fits all ballistic vests approach is often driven by budget considerations. Other considerations are related to limitations in size variations of ballistic vests that could create fit problems for firefighters with different body shapes and sizes. Poorly fitting gear can hinder mobility and limit the range of motion compromising the safety of the firefighters by reducing their active movement and agility [154].

It is significant that only 4% of firefighters responding to the survey received training on the wear and use of ballistic protective equipment by the fire department (Figure 6). The apparent lack of training could contribute to the inefficient use of ballistic vests by firefighters and could potentially compromise their safety. It could also contribute to physical discomfort in its use as well as equipment damage resulting in increased costs for replacement or repair. It might also result in improper use in the event of an emergency where firefighters might be unaware of extra weight, and movement restrictions added by ballistic vests which could hinder the firefighters’ response or make them more susceptible to injuries.

Fire departments typically recommend wearing ballistic vests for deployment scenarios that involve ballistic threats. Their purchasing decisions are nominally designed to provide ballistic gear that provides the maximum protection for firefighters, balanced with consideration of the cost of the PPE purchased. Given the potential urgency of emergency incidents, the need for training for active shooter situations is apparent. However, the lower percentages for other response scenarios, notably for EMS and response to working fires, indicate the need for more comprehensive training on firefighter use of ballistic gear. Therefore, it is critical to determine whether training sufficiently addresses the individual challenges and requirements of different deployment scenarios. For example, training for using ballistic vests when working with flames, or in conjunction with turnout gear, needs to be considered.

Our survey showed that ballistic gear is most often used in active shooter scenarios, a finding that is consistent with the focus on this response scenario in training. At the same time, our data showed that a high percentage of firefighters' reports wearing ballistic equipment only in training. This indicates that a significant portion of responders have not encountered deployment situations requiring the use of ballistic protection gear. This may be due to the relatively low frequency of response scenarios that call for the deployment of ballistic gear. However, the survey also showed that a substantial number of firefighters use ballistic protective equipment in EMS and civil unrest scenarios. This finding confirms the importance of training for the deployment of ballistic gear when it may be required in these responses. It also raises concerns regarding the efficacy of the training effectiveness in terms of translating into real-world usage. It would be useful to better understand why some firefighters

3.4.1: Ballistic vests for firefighters

Firefighters encounter a bewildering range of options when specifying and procuring ballistic vests. Different categories of ballistic vests provide different levels of protection against firearms; stab resistance against edged or pointed weapons; or combined protection against ballistic and stab threats. Manufacturers produce ballistic vests specifically for firefighters and EMS personnel, and they offer PPE options for both for law enforcement applications. Most commercially available ballistic vests for firefighter use are certified by the National Institute of Justice (NIJ). Content analysis showed that most of the ballistic vests for firefighters are soft armor.

A typical soft ballistic vest has front and back panels and an additional panel insert for added protection. There are also adjustable straps over the shoulders and around the waist to adjust to the length and girth of the torso. The materials used, the number of layers on the front and rear panels, and the thickness of the supplementary panels are chosen based on the threat levels. The front and back panels are usually constructed with multiple layers of aramid yarn-based bullet-resistant fabrics for soft ballistic vests.

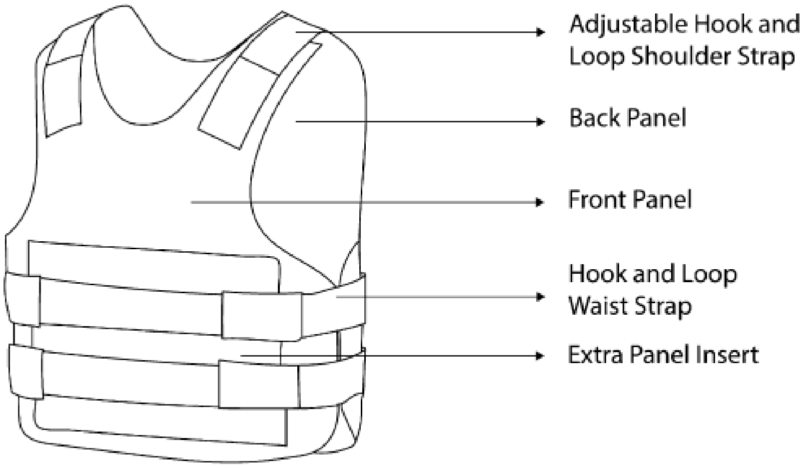


Figure 9. Structure of a basic ballistic vest [112]

According to the manufacturers, ballistic vests for firefighters are similar to the law enforcement officers in design apart from the fact that they are cut differently around the neck and armhole. For law enforcement officers, the neckline and armhole are cut in a round shape to optimize mobility and protection. For firefighters, the neckline and armholes are cut in a square shape for the convenience of manufacturing as square shaped neckline and armholes are easier to cut and sew than round shape. Since firefighters do not have to move or hold guns in a specific posture, the square neckline and armhole do not hinder their range of motion and mobility whereas round shaped neckline and armhole provide more coverage and range of motions for the law enforcement officers.

3.4.2: NIJ Levels for Ballistic Vests:

The National Institute of Justice (NIJ) establishes ballistic resistance criteria for personal ballistic vest (NIJ Standard 0123.00, 2023). Market research showed that ballistic vests for firefighters are also NIJ-certified and maintain NIJ threat levels. NIJ threat levels indicate the levels of protection provided by different types of ballistic vests against certain ballistic threats. The NIJ ballistic threat categories are IIA, II, IIIA, III, and IV, with each level providing increased protection against heavier caliber gunfire. These threat levels provide guidelines for the selection of proper ballistic vests based on the specific hazards the firefighters might encounter. While these levels provide uniform classification for protection, the performance of ballistic vest is also dependent on factors such as materials, fit, and the design details of the overall ballistic system.

Vargas (2016) assessed the effect of wearing ballistic vests underneath firefighter turnout gear based on the threat level. The lower the threat level, the lower the weight of the ballistic vest. Therefore, as would be expected, lower weight ballistic vests offered the least amount of protection (Levels II and III), although it provided more flexibility and had less impact on performance. Conversely, heavier-weight ballistic vests provided the maximum amount of ballistic protection (Level IV) at the expense of mobility and heat strain.

3.4.3: Performance guidelines for the selection and use of ballistic vests by firefighters

Our survey data showed that 81% of firefighters surveyed shared or were issued ballistic vests by the fire department (Figure 5) and Table 1 showed that firefighters use ballistic vests that are NIJ certified with threat level IIIA. Nevertheless, policies on the procurement and deployment of ballistic vests by fire departments vary in fire departments across the country [5]. Little documented information is available on how firefighters wear ballistic vests with turnout gear or station uniforms. Because these factors affect firefighter heat stress, mobility, and thermal protection in emergency response, this is a critical gap in available information.

The ASTM E3348 recommends ballistic gear that provides at least level IIIA protection based on the ability to stop bullets, as certified to the NIJ Standard-0101.06 standard for non-law enforcement applications [9], [111]. ASTM E3348 also recommends studies to understand whether additional ballistic protection causes more harm than good in terms of heat stress, since there are no existing scientific studies regarding this. ASTM E3348 suggests wearing ballistic vests under turnout suits to protect ballistic vests against the hazards of flammable or thermoplastic components. It cites no study on the efficacy of this approach, nor does it identify testing protocols to assess the effect of ballistic gear on thermal protective performance in fire environments. It also suggests the use of fire-resistant clothing with ballistic vests without identifying clothing ensemble options or describing how ballistic vests may be included in an effective multi-threat ensemble for firefighters.

In many ways, the ASTM E3348 guidelines reflect the contradictory set of circumstances now faced by fire departments across the country. They are increasingly required to issue and train firefighters and EMS personnel on the selection and use of ballistic gear in emergency response while lacking the basic information on the trade-offs of using it with firefighting gear, particularly from heat stress or burn injuries. They lack the scientific data about performance trade-offs needed to develop best practices for using ballistic gear when this PPE is needed in firefighting or EMS response.

NFPA 3000 standard identifies threats for firefighters in active shooting scenarios as hot, warm, and cold zones [14]. The hot zone is an area where there is a known, direct, and immediate life threat. PPE is included but is not limited to ballistic protection equipment (BPE). The warm zone has the potential for a hazard or an indirect threat to life. PPE is included but is not limited to BPE. The cold zone has little or no threat due to its geographic distance from the threat. An identifying garment or visible identification is recommended for this zone. NFPA 3000 recommends BPE for fire and EMS personnel to be NIJ certified and at least at NIJ level IIIA as tested according to NIJ 0101.06 standard. NFPA 3000 also recommends that integrated response teams use ballistic helmets, and carry a flashlight, medical exam gloves, and an individual first aid kit. PPE and BPE worn externally should be identified with the agency or responder role. BPE care, maintenance, and replacement practices should follow NIJ 0101.06.

3.4.4: Effects of ballistic vests on interoperability of firefighter gear

Our content analysis (Table 1) showed that interoperability plays an important role in terms of choosing ballistic vests for firefighters. Many fire departments use a situation-based policy that requires firefighters to wear ballistic vests whenever violent activities may occur at a scene, including response to incidents of domestic violence, active shooting, and warm zone operations [155], [156], [157]. Since shooting incidents are unpredictable, some departments mandate wearing ballistic vests for all EMS personnel on emergency calls [155]. Other departments require ballistic vests for firefighters on all emergency calls (Firehouse, 2013). When responding to non-fire emergencies, emergency medical responders usually wear ballistic vests over their station uniforms. If a firefighter is required to wear a ballistic vest with their turnout gear, they typically wear it under the turnout jacket [16]. However, some fire departments recommend only wearing ballistic vests over turnout suit [156].

Many studies have shown that ballistic vests significantly affect the performance of operational tasks when worn in military and law enforcement applications (Dempsey et al., 2013; Loverro et al., 2015; Park et al., 2011; Taylor et al., 2016). However, these findings do not translate to ballistic vest effects on firefighters and EMT job performance as they perform distinctly different tasks wearing different PPE than soldiers and law enforcement personnel. It is significant that no systematically conducted ergonomic studies currently provide an assessment of the interoperability of ballistic vests with essential elements of firefighter gear as well.

3.5. Effect of ballistic vests on responders

3.5.1: Effects of ballistic vests on responder heat strain

While it is logical to assume that deploying ballistic vests can have deleterious effects on firefighter mobility, no studies yet exist on the possible effects of heat strain on firefighters. There is a gap in our understanding of how to wear ballistic vests in combination with a turnout suit. This knowledge gap is compounded by the general lack of studies that focus on female disparity in terms of available and correctly fitting PPE.

Most departments advise wearing ballistic gear underneath a turnout to protect the gear from the heat that can melt or degrade the materials and components used in its construction [163]. However, some fire departments wear ballistic vests over turnout suits. These examples of conflicting approaches to wearing ballistic vests with turnouts underscore the need for a scientifically considered study on the effect of gear configuration on factors of fit, ergonomic functionality, and physiological heat strain.

Numerous studies have been conducted on the effects of turnout design, materials breathability, and environmental conditions on firefighter heat stress, ranging from using advanced thermal manikins to measure heat transfer through firefighter garments to the application of physiological models to predict human heat stress response [65], [164], [165], [166]. These studies showed that adding moisture vapor impermeable components to turnout suits significantly reduced heat loss by sweat evaporation from the human body [164]. This is a significant finding because a ballistic vest covers a sizeable fraction of skin area; about 50% of the skin surface in the torso area of the body [167]. Since heat loss from sweat evaporation is a major mechanism of cooling the body, it is reasonable to expect that wearing a ballistic vest that covers a significant portion of the skin surface will have a significant effect on the firefighter's heat strain.

Wearing ballistic vests adds to firefighter heat strain, not only by adding thermal insulation and evaporative resistance to PPE but also by adding weight to the clothing ensemble. Military laboratories have extensively studied these effects; wearing a military ballistic vest over a duty uniform reduced work tolerance time by one-half, with major deleterious effects caused both by the increased thermal insulation and evaporative resistance and by the weight of the vests [168]. Because of the obvious differences in military and firefighter gear, and the differences in use conditions, findings from military studies cannot predict the heat strain of ballistic vest for firefighter applications.

Therefore, there is a need for research to determine how much heat strain is caused by wearing ballistic gear for firefighters in different environmental conditions. This would provide the technical foundation for operational decisions that can result in reducing the heat stress hazard to firefighters and EMS in situations where they wear ballistic vests. It would show how different combinations of wearing ballistic vests with firefighting gear can affect firefighter heat stress. This information is needed for the optimum deployment of ballistic vests specifically for firefighter operations. It would help firefighters select ballistic vests and manage work protocols to reduce heat strain.

3.5.2: Effects of ballistic vests on potential burn injury

According to the ASTM Guide to Body Armor for Non-Law Enforcement Applications, if they choose to wear body armor/ballistic vests with turnout suits, firefighters should wear the gear under their turnout to protect flammable or thermoplastic components in the ballistic vest construction [9]. However, the guide does not provide evidence of the efficacy of this approach or identify testing protocols to assess the effect of ballistic gear on flammability in fire environments. It also suggests using other fire-resistant clothing with ballistic vests without identifying clothing options. It does not account for instances where firefighters may wear their ballistic vests over their turnouts thereby directly exposing the ballistic gear to intense heat and flames. It does not consider the burn injury hazard presented to responders by flaming liquids (e.g., Molotov Cocktails) hurled at them. There have been several recent reports of firefighters and first responders being attacked with Molotov Cocktails or fires started by Molotov Cocktails [169].

The discrepancy between the heat resistance requirements of turnout suits certified to the NFPA 1971 standard and the lack of any thermal performance requirements for ballistic vests are apparent. The NFPA 1971 Standard requires that all components used in the construction of turnout suits meet minimum flame and heat resistance requirements as demonstrated in flammability tests and by five-minute exposure to 500F in an oven test (NFPA 1971, 2018). In contrast, there are no current requirements that ballistic vest, worn by firefighters in fire environments, be tested to demonstrate that it meets minimum flammability and heat resistance levels. This is an important safety consideration, particularly because the low level of heat and flame resistance of materials used in some ballistic vest raises questions about their use in fire environments. Some soft ballistic vests, known for their lightweight ballistic performance, contain high molecular weight polyethylene that melts at about 150°C, far below the temperatures possible in a fire environment [171]. Thermoplastic fibers, such as nylon and polyester fibers are in ballistic plate/vest carriers or hook and loop straps. These thermoplastic materials could melt and lose strength if exposed to the temperatures routinely encountered in firefighting operations.

Therefore, the flammability of ballistic vests should be an issue of significant ongoing concern to firefighter safety. The questions that need to be addressed include: Does wearing ballistic vests made from non-FR or non-heat-resistant materials in fire environments constitute a burn injury risk to firefighters in fire suppression activities? Does wearing ballistic gear under a turnout suit mitigate the burn injury risk, even if some of the components used in the construction of ballistic vests are thermoplastic materials, such as polyester, which melts at relatively low temperature.

3.5.3: Disparity of Female Firefighters in Research Studies

In 2018, there were an estimated 93,700 (~8%) female firefighters in the United States [172]. Additionally, approximately 21% of EMS paramedics are female, and they had a 23% growth from 2012-2022 [173]. Despite differences in gender, female firefighters and emergency responders are expected to perform the same duties as their male counterparts, however, they often deal with gear and equipment that was designed for the male form.

Despite the growth and equal expectations of performance, there are few studies of firefighter and EMS PPE that include considerations for the differences between the male and female forms. Especially apparent with PPE, functionality, and performance can be compromised due to the need for a female to use a male-designed system. For maximum protection, ballistic vests should fit snuggly against the wearer to maintain the levels of protection afforded by the vest [9]. The ASTM guide for ballistic vests in non-LE applications does have a note that indicates that ballistic vest sizing may be different between men and women and includes a reference to ASTM E3003 which provides guidance for measuring a ballistic vest wearer for both male and female personnel. It also states that body shape should be considered. Similar to firefighter turnout suits, ballistic vests may impact females differently, and considering potential differences will be a fundamental part of this research effort.

Most firefighter turnouts today are designed for the male size and shape, leaving female firefighters to choose between the best-fitting sizes available. This can often lead to poor fitting PPE for women firefighters. Loose, bulky, tight, and uncomfortable PPE can have a significant impact on firefighter performance and can ultimately increase the probability of compromising the health and safety of the firefighter. Firefighter research studies typically only consider male anthropometry in the development, testing, and experimental conclusions. Unfortunately, this causes the conclusions and outcomes to be less valid for a growing portion of the fire service population.

3.6: Conclusion

Firefighters wear ballistic vests in high-risk operations where there is a strong likelihood of encountering gunfire and ballistic threats. Apart from that, firefighters need to wear ballistic vests to simulate real-world situations and train themselves to become accustomed to the use and limitations of the equipment. Our survey found that about 80% of fire departments had ballistic protective equipment, including ballistic helmets, armor plates, and vests. Because of differences in body shapes and forms, most of the shared ballistic gear among firefighters may cause fit problems. Also, training on the use of this equipment was lacking, with a large number of respondents receiving minimal to no training. In addition to insufficient training, the actual use of ballistic protection varied among the firefighters. While many of the firefighters had worn ballistic gear several times, a significant number had worn it only once. Overall, the survey highlighted the need for more extensive training and better knowledge of the factors influencing firefighters' use of ballistic vests in various operating settings.

There is an ongoing need for a better understanding of performance tradeoffs associated with firefighter selection and use of ballistic vests. More information is needed about current use practices and conditions commonly associated with different response scenarios. There is an additional need for studies of the effects of ballistic vests on firefighter heat strain and mobility, and how wearing ballistic gear, with or without a turnout suit affects these factors, for both male and female firefighters. This survey study not only provides useful information to firefighters and responders but also casts a light on the importance of ballistic vests for firefighters and how broadly they are being used by firefighters across the United States.

CHAPTER 4

METHODOLOGY

Understanding how firefighter protective ensembles interact with added ballistic protection requires a methodological approach that integrates. This chapter describes the experimental and computational methodology developed to address this critical gap.

The methodological framework was designed to achieve two overarching goals:

(1) to measure the thermal insulation (R_t) and evaporative resistance (R_{et}) of firefighter ensembles with and without ballistic protection, and

(2) to model the resulting physiological impact on male and female firefighters under realistic environmental and activity conditions.

4. 1 Experimental Methods

4.1.1 Thermal sweating manikins

Thermal resistance (R_t) and evaporative resistance (R_{et}) were examined using thermal manikin Newton and Liz respectively. Newton is designed as a male thermal manikin that represents the average male body dimensions (5’10” height and body surface are 1.86 m^2) whereas Liz is a female thermal manikin representing average female body dimensions (5’5” height and total body surface area 1.62 m^2). Newton’s body surface area (1.86 m^2) is about 15% larger than Liz’s (1.62 m^2), he has a greater total area for convective, radiative, and evaporative heat exchange. According to Del Ferraro et al. (2017) Newton is used with 50th percentile Western male body form [174]. When comparing their results directly, any differences in thermal resistance (R_t) or evaporative resistance (R_{et}) could partly stem from this size difference, not only from ensemble or anatomical differences. Both manikins have 30 independently controlled thermal zones to measure heat flux and skin temperature across different parts of the body and are capable of simulating metabolic heat generation, and sweating. Both Newton and Liz comply with major standards relevant for clothing thermal and evaporative resistance testing: ASTM F1291, F1720, F2370, F2732; ISO 15831 [55], [175]. Both male and female manikins were used to measure the parameters thermal resistance, evaporative resistance, and total heat loss.

Figure 20. Male manikin (Newton) and female manikin (Liz)

Newton’s larger surface area can yield higher absolute heat loss, meaning whole-body R_t and R_{et} differences may partially reflect geometry rather than clothing performance alone. Newton’s flatter torso promotes tighter, more uniform garment contact, while Liz’s contoured geometry increases spatial variability in air-layer thickness. Liz is more likely to develop localized insulating air pockets or vertical ventilation channels, depending on garment design or fit, which can simultaneously increase thermal insulation and alter evaporative resistance.

4.1.2 Thermal Modeling

Using thermal insulation and evaporative resistance data, thermal modeling were conducted using TAITherm software to obtain physiological responses for each ensemble. TAITherm is an advanced 3D thermal and physiological modeling software widely used in human factors research, protective clothing evaluation, and environmental factors to simulate heat transfer and thermoregulatory responses under controlled or dynamic conditions [176]. Built on the validated Fiala thermophysiological model, which is a multi-node, multi-layer system shown to accurately predict core temperature, skin temperature, and cardiovascular responses across diverse environments [177]. TAITherm integrates conduction, convection, radiation, and evaporative heat exchange with clothing insulation properties, metabolic rate, and ambient conditions. Numerous studies have demonstrated that the Fiala model [177] produces physiologically reliable predictions comparable to human subject trials, particularly in heat-stress scenarios and encapsulating protective ensembles. Therefore, TAITherm is an appropriate tool for this study because it allows experimental manikin-derived R_t and R_{et} values to be coupled with a scientifically validated physiological model, enabling realistic prediction of thermal strain and gender-specific responses in conditions where human subject testing would be unsafe or impractical in extreme ambient conditions. The software operates by combining heat transfer mechanisms including conduction, convection, radiation and evaporation. The parameters that are incorporated by this software are gender, heigh, weight, metabolic rate (activity level), clothing properties (thermal insulation, evaporative insulation, clothing area factor), environmental factors (temperature, humidity, wind speed, etc.) to predict human physiological responses (core temperature, mean skin temperature, heart rate, etc.) in the given circumstances. For this study, physiological responses for both male and female will be obtained by using the simulation modeling software and a validation analysis of the model will be conducted.

4.2 Test materials (ensembles)

In order to quantify the thermal insulation, six combinations of firefighting ensembles were selected: E1) station uniform (Baseline 1); E2) station uniform and ballistic vest; E3) station uniform and turnout suit (Baseline 2); E4) station uniform, turnout suit and ballistic vest worn under the turnout jacket; E5) station uniform, turnout suit and ballistic vest worn over the turnout jacket; E6) station uniform, turnout suit and ballistic vest with hard plates worn over the turnout jacket. The six ensembles (E1-E6) were selected directly from patterns identified in our national firefighter survey (chapter 3), which showed that firefighters typically wear ballistic vests in three operational contexts: over the station uniform, beneath the turnout jacket, or over the turnout jacket. Level IIIA soft ballistic vest and Level IV hard-plate systems were included because they represent the two threat levels most frequently reported by respondents. By combining these elements, the ensembles capture the full range of real-world configurations currently used in fire, EMS, and civil-unrest scenarios. This structure allows clear comparison between baseline conditions (E1, E3) and the incremental thermal burden added by soft and hard armor in both under and over turnout jacket placements.

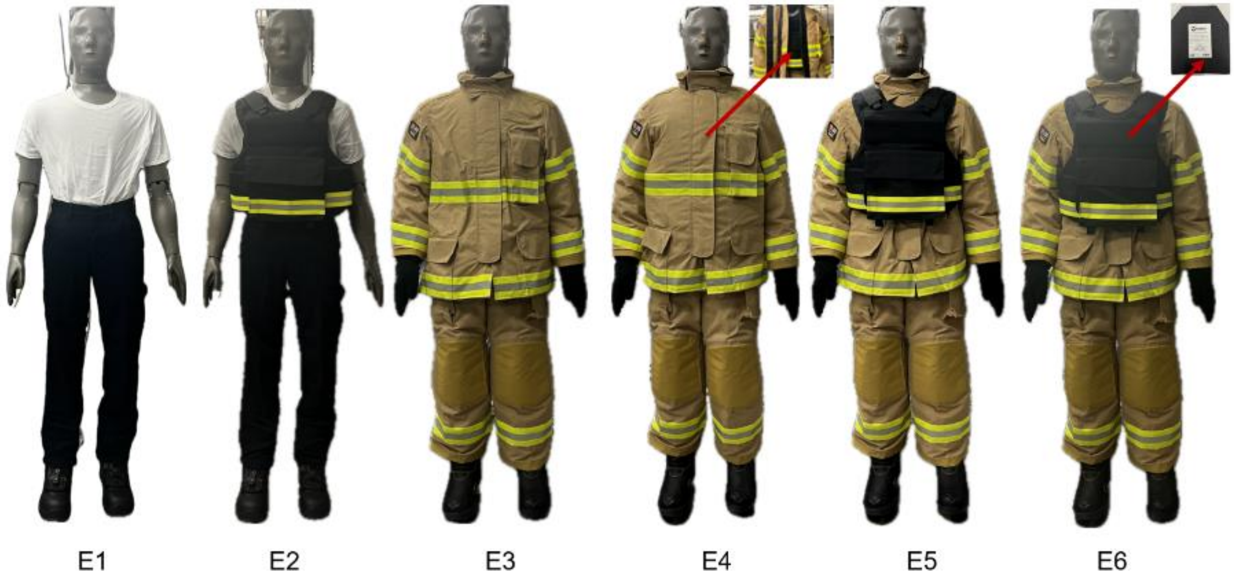


Figure 21. Schematic of test ensembles

The turnout suit selected for this research represents a contemporary, NFPA-compliant structural firefighting ensemble and was intentionally chosen to provide a realistic and standardized baseline for evaluating thermal and evaporative performance. The layering of turnout suit is consisted of a para-aramid/meta-aramid outer shell (65% Kevlar, 35% Nomex), a PTFE-laminated aramid moisture barrier (Crosstech), and a quilted thermal liner composed primarily of aramid fibers (93% aramid, 7% rayon) reflects materials and assemblies widely used in U.S. fire service PPE. Each layer has well-characterized thermophysical behavior: the aramid outer shell provides flame resistance and structural durability with minimal moisture sorption; the PTFE moisture barrier governs vapor transport and is a dominant contributor to evaporative resistance; and the aramid-based thermal liner supplies consistent insulation while allowing limited moisture buffering. Using this established turnout system ensured repeatable dry and sweating manikin measurements and enabled direct comparison with prior literature and standards-based benchmarks. Importantly, the use of conventional turnout ensembles minimized material-related confounding effects, allowing observed changes in thermal resistance, evaporative resistance, predicted heat loss, and physiological strain to be attributed primarily to the addition of ballistic body armor rather than to atypical turnout materials, thereby strengthening the external validity and translational relevance of the findings.

The NIJ-certified Level IIIA ballistic vest was selected for this study because it represents the most realistic and operationally relevant form of ballistic protection currently worn by firefighters during non-military threat scenarios. Level IIIA ballistic vest is specifically designed to protect against common handgun threats (e.g., 9 mm and .44 Magnum), which align with the types of ballistic risks firefighters may encounter during active-shooter responses, civil unrest, law-enforcement support, and EMS-related incidents, rather than rifle-level threats that would necessitate heavier, hard-plate armor. As such, Level IIIA vests are the most frequently issued and practically deployable ballistic option for fire service personnel. From a research perspective, the use of a NIJ-certified vest ensured that the ballistic system met recognized national performance and construction standards, thereby grounding the study in real-world PPE configurations rather than experimental or hypothetical armor systems. This choice was essential for maintaining external validity and for ensuring that observed changes in thermal resistance (R_t), evaporative resistance (R_{et}), predicted total heat loss (THL), and physiological strain could be directly attributed to a legitimate, field-ready ballistic ensemble.

The details of the test ensembles are in the following table:

Table 4. List of ensembles

Ensembles	Configuration details	Total weight (kg)
E1	**Station Uniform** (100% cotton t shirt, dress pants, boxershorts, socks, station boots)	3
E2	**Station Uniform + Ballistic Vest IIIA Overt** (100% cotton t-shirt, dress pants, boxershorts, socks, station boots, ballistic vest IIIA)	7.2
E3	**Station Uniform + Turnout suit** (100% cotton t-shirt, dress pants, boxershorts, socks, turnout suit over station uniform, turnout boots)	8.32
E4	**Station Uniform + Turnout suit + Ballistic Vest IIIA Overt** (100% cotton t-shirt, dress pants, boxershorts, socks, turnout suit, turnout boots, ballistic vest IIIA over the turnout suit)	12.5
E5	**Station Uniform + Turnout suit + Ballistic Vest IIIA Overt** (100% cotton t-shirt, dress pants, boxershorts, socks, turnout suit, turnout boots, ballistic vest IIIA over the turnout suit)	12.5
E6	**Station Uniform + Turnout suit + Ballistic Vest IV (with hard plates-front & back) Overt** (100% cotton t-shirt, dress pants, boxer shorts, socks, turnout suit, turnout boots, ballistic vest IV over the turnout suit)	20

Among the ensembles, E1 and E3 will be considered as controls and E2, E4, E5, and E6 will be variables. The control ensembles do not have any ballistic vests, and the variables have ballistic vests with two threat levels (level IIIA and IV).

4.3 Experimental approach

The research design was structured into the following four tasks. Tasks 1 and 2 correspond to research questions 1 and 2. Task 3 and 4 address research questions 3 and 4. These 4 tasks will be conducted in two phases. Tasks 1 and 2 will be included in Phase 1 and tasks 3 and 4 will be under Phase 2.

Phase 1: In this phase, lab experiments were conducted to answer research questions 1 and 2. Both dry and wet tests were conducted to determine thermal resistance and evaporative resistance of the clothing ensemble.

The dry and wet tests were conducted on a male and a female manikin in the Textile Protection and Comfort Center at North Carolina State University. There are three primary methods to assess the thermal and evaporative resistance of a textile fabric or garment- sweating guarded hotplate, sweating thermal manikin, and human subjects [49]. Studies showed that thermal manikin measurement yields a more realistic value than a sweating-guarded hotplate [52]. Thermal manikin can assess the impact of clothing's boundary air layers and investigate the role that design elements play in the evaporative resistance of clothing. Measuring the steady-state rate of evaporative heat loss and the water vapor pressure differential between human skin and ambient air are two ways to accomplish the third strategy described above [49]. Therefore, to accurately evaluate the thermal comfort of clothing and the environment, the thermal manikin is a vital tool for understanding heat exchange between the human body and the environment. By correctly measuring the heat exchange between the human body and its surroundings, the thermal response of the human subject in the environment was anticipated based on human physiology by using thermal sweating manikin.

Task 1. Identifying and establishing controls and variables of firefighter clothing ensembles for experimental design

The aim of task 1 was to identify and establish clothing ensembles for firefighters that include station uniform, firefighting turnout suits and ballistic vests. Two sets of station uniform, and turnout suits were purchased for both male and female manikins. One size adjustable level IIIA ballistic vest was used for both male and female manikins. Hard plates were inserted in the front and back of level IIIA ballistic vest to convert it into level IV. All the ensembles were tested to assess their thermal and evaporative resistance. Expected outcomes from task 1 are the identification of the clothing ensembles that are mostly used by the firefighters in real world, establishing control (non-ballistic) and variables (including ballistic vests) to quantify the amount of heat strain caused by ballistic vests and identifying significant variables affecting heat strain and performance.

Task 2. Assessing the thermal insulation and evaporative resistance properties of ballistic vests in comparison to standard turnout gear

Task 2 aimed to quantify the thermal insulation and evaporative resistance of the clothing ensembles. In order to measure thermal resistance, a dry test was conducted following ASTM 1291. Wet test was performed to assess evaporative resistance of the clothing ensembles following ASTM F2370. Each ensemble was tested three times, and the average were taken in both tests. In the dry test, intrinsic resistance of clothing and total thermal resistance of the system were calculated. The results provided insights into how clothing ensembles prevent heat transfer from body to the environment. In the wet test, total evaporative resistance and predicted total heat loss were calculated. The results provided an insight into which clothing ensembles have higher breathability. The results from phase 1 were used as the input for virtual simulation in Phase 2. Expected outcomes are identifying which clothing ensemble would cause more heat strain to the firefighters by comparative analysis; insights into the level of heat stress caused by clothing ensembles and understanding of mechanisms underlying reasons for heat strain caused by each ensemble.

Phase 2: The data acquired from lab tests (task 2) was used for thermal modeling in this phase using TAITherm^{TM} 3D thermal simulation software that predicts temperatures using transient or steady-state analysis. The simulation was conducted using selected ensemble data from dry and wet tests, controlled ambient parameters (temperature, humidity, wind speed used in dry and wet tests), and different activity levels (resting and walking).

Thermal modeling process can be divided into three parts: independent variables, dependent variables and output. The process diagram is as follows:

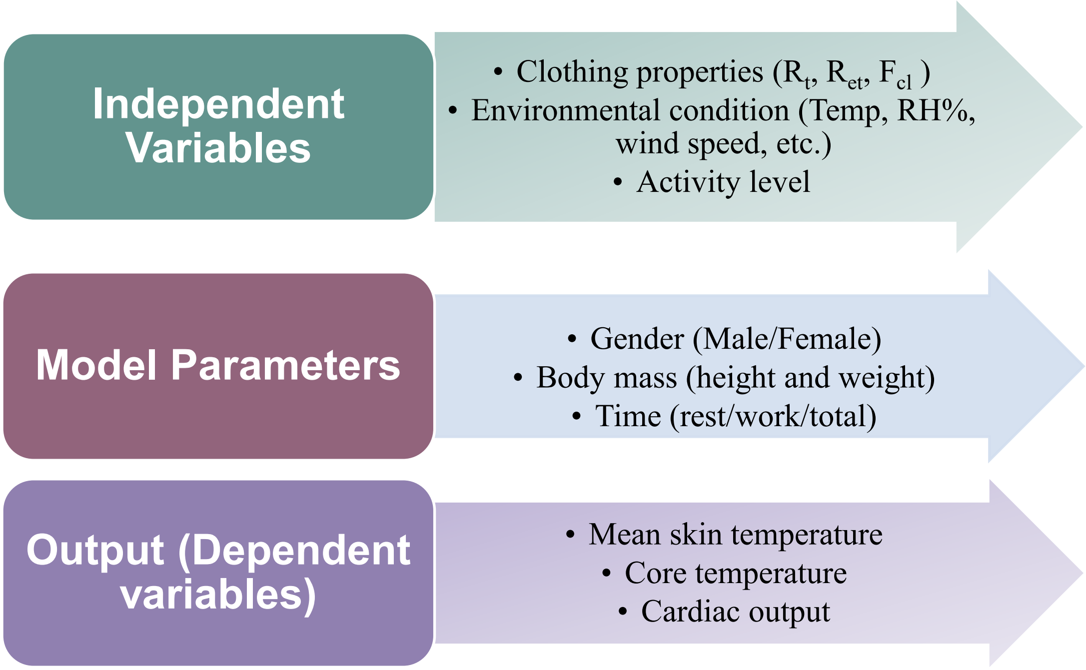


Figure 22. Experimental approach for thermal modeling

Task 3. Exploring how load, duration and intensity of firefighting activities impact heat strain in males and females wearing the combined gear

The aim of task 3 was to understand physiological responses for different clothing ensembles using the lab test data. The simulations were conducted using TAITherm software for each ensemble using male and female manikin data.

There were three inputs for the software, 1) clothing properties; 2) ambient conditions; and 3) activity levels. For clothing properties, each ensemble had both thermal and evaporative resistance data from lab tests. The model parameters which needed to be set were gender (male and female), body mass (different height and weight), ambient conditions (temperature and humidity), and activity level. The activity level included resting and walking, and the metabolic rate will range from 1.1 MET (resting)- 3.5 MET (walking) as they represent the most common metabolic states reported by firefighters during ballistic-related call types and periods of low activity during standby or assessment, followed by moderate activity during movement, evacuation, or scene response [178], [179]. These workloads also align with established physiological modeling ranges for evaluating heat strain in protective clothing. Variations in work–rest cycles were incorporated to replicate the stop and go nature of real emergency operations and to capture transient thermal responses rather than only steady-state outcomes. This approach allowed the model to evaluate how heat strain accumulates or dissipates across operationally realistic fluctuations in workload. Effects of each variable were assessed on physiological responses. From the simulation, mean skin temperature, core temperature, and cardiac output were extracted. Expected outcomes from this task were identification of thresholds for safe operation; insights into the influence of activity intensity and duration and understanding of the impact of load gear on physiological stress.

Task 4. Comparing physiological responses between males and females using simulation data while wearing while wearing ballistic vests with firefighting gear

Task 4 investigated differences in physiological responses (core temperature, mean skin temperature, and cardiac output) between males and females. The findings provided insights into how males and females respond while wearing the same clothing ensemble in the same environmental conditions and activity levels. Expected outcomes were insights into the physiological differences between male and female under heat strain and load carriage; understanding metabolic differences between male and female; and identification of statistical significance of gender differences.

4.4. Project Measurement and Analysis

4.4.1. Measurement for thermal resistance

Dry tests were conducted to assess thermal resistance of the clothing ensembles on both male and female manikins. The lab was conditioned according to the ASTM 1291 standard. The manikin was set to maintain a uniform temperature distribution over the nude body surface, with no local hot or cold spots. The mean surface (skin) temperature of the manikin was 35 °C. Local deviations from the mean skin temperature did not exceed ∓0.5 °C. The air temperature was 15°C. The air velocity was 0.4∓0.1 m/s during the test. Relative humidity was 55-58%. However, the relative humidity has no effect on measurements of thermal resistance under steady state conditions [180].

Calculating thermal resistance from manikin tests

After the nude test was done, all six configurations were tested for the dry test. Nude tests on thermal sweating manikins are a necessary baseline step before measuring clothing thermal resistance (Rt) and evaporative resistance (Ret) because they establish the reference heat and mass transfer characteristics of the manikin itself, independent of clothing. Without this baseline, clothing insulation and vapor resistance cannot be quantified accurately. For our research project, $R_{t,}$ and $R_{cl,}$ were measured for torso area only and whole ensembles.

Where,

R_t = total thermal resistance (insulation) of the clothing and surface air layer around the manikin (°C·m2 /W),

R_{cl} = intrinsic thermal resistance (insulation) of the clothing (°C·m2 /W),

A higher R_t indicates a higher resistance and less heat transfer of the system. R_{cl} provides insights into how much the clothing itself contributes to the resistance without the effect of the surrounding air layer.

4.4.2. Measurement for evaporative resistance

To measure evaporative resistance, the wet test was performed on both male and female manikins following ASTM F2370−22 standard on the same manikin used for the dry test. For this test, pre-wetted tightly fitted fabric skin was put on the manikin that mimic human skin. The manikin was set to maintain a uniform temperature distribution over the nude body surface, with no local hotter or colder spots than 35°C∓ 0.5°C. The mean surface (skin) temperature of the manikin should be 35 °C. Local deviations from the mean skin temperature did not exceed ∓0.5 °C. The air temperature was 35°C. The air velocity was 0.38 to 0.4 m/s during the test. The relative humidity was 40%.

Calculating evaporative resistance from manikin tests

For our particular research project, $R_{et,}$ R_{ecl} and $Q_{predicted}$ were measured.

Where,

R_{et} = total evaporative resistance (insulation) of the system (m^2Pa/W)

R_{ecl} = intrinsic evaporative resistance (insulation) of the clothing (m^2Pa/W),

$Q_{predicted}$ = Predicted total heat loss ($W/\ m^2$),

The higher R_{et} indicates greater resistivity of moisture meaning less breathability of the clothing and vice versa. On the other hand, higher $Q_{predicted}$ indicates better evaporative cooling and vice versa. R_{et} and $Q_{predicted}$ are inversely related. A lower R_{et} (better breathability) usually results in a higher $Q_{predicted}$ which means when more sweat can evaporate, the body can cool down more efficiently.

4.4.3. Measurement for activity level using metabolic equivalent (MET)

Activity level was both estimated and set using MET value that quantified energy expenditure relative to resting metabolism [129]. Load carriage is a core requirement of personnel serving in various physically demanding occupational settings, particularly firefighting [131]. These heavy loads with intense physical activities increase the activity level as well as the risk of hyperthermia, hypohydration, under-nutrition, and degraded mental and physical work capacities [114]. Mathematical algorithms that predict the metabolic cost of various physical activities are at the heart of occupational mission planning and safety assessment tools (e.g., establish work-rest cycles, water requirements, etc. [98]. To accomplish tasks 3 and 4, MET was calculated for both males and female using Pandolf equation. The numerical values of MET were incorporated into TAITherm Software to evaluate physiological responses such as core temperature, mean skin temperature, and cardiac output.

The Pandolf Equation

The Pandolf Equation is a mathematical formula used in exercise physiology to estimate the metabolic energy expenditure (calories burned) during various physical activities. It takes into account different factors such as the individual's body weight, the efficiency of movement, and the intensity of the activity to estimate energy expenditure. The Pandolf equation can be stated as follows:

$$M_w = 1.5W + 2(W+L)(L/W)^2 + \eta(W+L)[1.5V^2+0.35VG]$$

where,

M_w= metabolic rate (watt)

W= nude body weight (kg)

L= clothing and equipment weight (kg)

η= terrain factor

V= walking velocity (ms^{-1})

G= grade (%)

Metabolic rate was converted to Metabolic equivalent (MET) using the formula below:

$$MET = Metabolic\ rate\ (watts)/Body\ weight\ (kg)x\ 1.162$$

MET was estimated for each ensemble for both male and female. The numerical value of MET was used as an input for the TAITherm software to evaluate physiological responses such as core temperature, mean skin temperature and cardiac output.

4.5 Simulations for physiological responses

Simulations were conducted for 50th percentile male (1.7 m height & 78 kg weight) and 50th percentile female on (1.6 m height & 65 kg weight) using TAITherm software .This approach ensured the representation of “average” individual of each gender in a given population. The simulation of both 50th percentile male and female demonstrated an overview of how differences in body size, shape, and physiological features influence the outcome.

Core temperature and mean skin temperature were measured in °C. Cardiac output was recorded in L/min for each ensemble for both males and females and comparative analysis was performed.

4.5.1. Analysis

Data were analyzed and compared to identify the differences in physiological responses between males and females in different conditions. The data between were compared to assess the following:

1. Effect of gender
2. Effect of work-rest time
3. Effect of environmental conditions (different temperatures and RH%)
4. Effect of activity levels
5. Effect of extreme height and weight

CHAPTER 5

RESULTS & DISCUSSION

This chapter presents the results and discussion of the experimental and computational analyses conducted to evaluate the thermal and evaporative performance of firefighter protective ensembles with integrated ballistic protection. Using Newton (male) and Liz (female) thermal manikins, six ensemble configurations were systematically assessed to quantify thermal insulation (R_t) and evaporative resistance (R_{et}), providing objective measures including clothing microenvironment. These laboratory-derived parameters were subsequently incorporated into physiological modeling to predict core temperature, mean skin temperature, and cardiac output under different environmental and metabolic conditions. By directly comparing outcomes between male and female manikins, this chapter not only highlights ensemble-level differences but also examines the influence of anatomical variation on heat transfer and strain. The overall objective is to integrate physical and physiological evidence to determine how ballistic vests, when combined with firefighting ensembles, alter thermal burden and cardiovascular responses in a gender-specific manner, thereby advancing the scientific understanding needed to optimize protective equipment design and inform firefighter safety standards.

5.1 Lab experiment (Task 1 & 2 results)

5.1.1 Dry test results (Male manikin)

The thermal resistance (R_t) values for E1, E2, E3, E4, E5, and E6 in the torso areas were 0.166, 0.331, 0.463, 0.622, 0.652, and 0.631 $m^2{\cdot}°C{\cdot}W^{-1}$ respectively (Appendix D). The results evidently depicted a progression of thermal resistance values in the torso area with adding layers.

R_t increased from 0.166 $m^2·°C·W^{-1}$ in E1 (baseline-without ballistic vest) to 0.331 $m^2·°C·W^{-1}$ in E2 (with ballistic vest added).

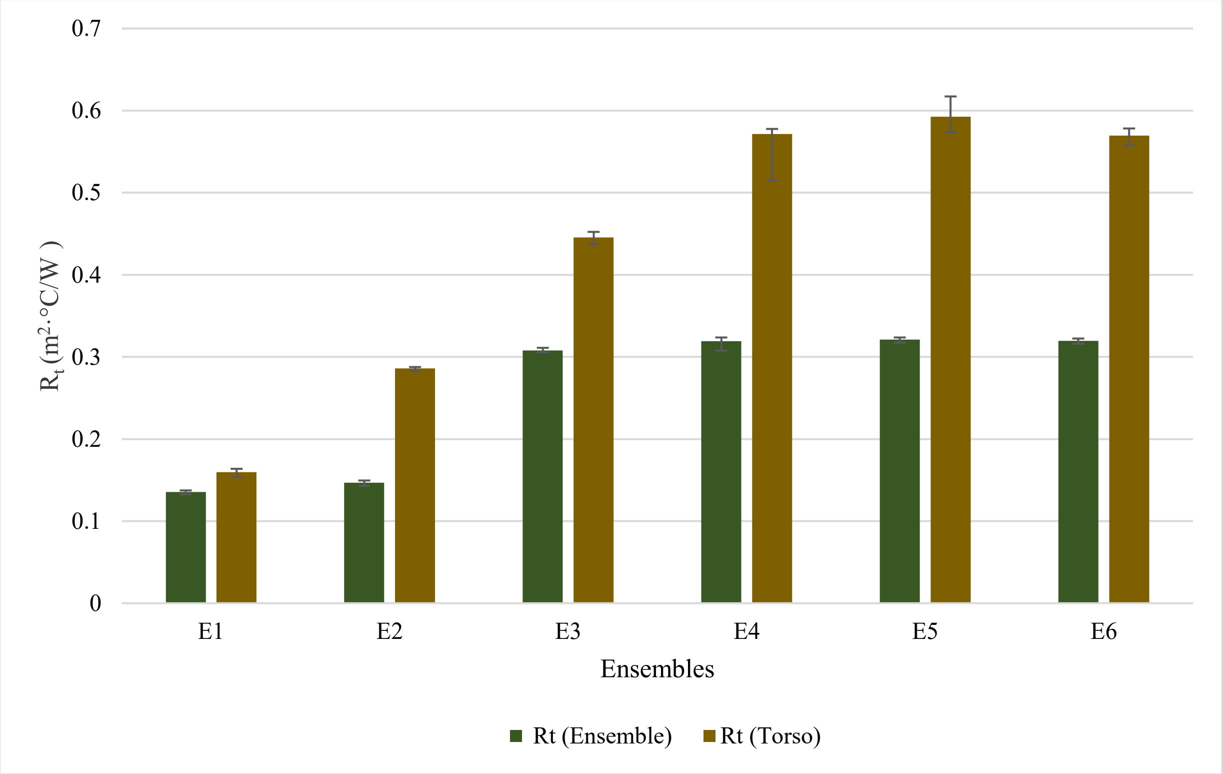


Figure 23. Thermal resistance of firefighting clothing ensembles in conjunction with ballistic vest on male manikin

The relative increase in R_t from E1 to E2 is approximately 99% on the torso, which indicated twice the thermal resistance with the addition of the ballistic vest. The further increase in R_t through E3 to E6 up to 0.652 $m^2·°C·W^{-1}$ demonstrated the compounding effect of additional layers in the firefighting turnout ensemble. The substantial increase in R_t from E1 to E2 is due to the dense materials (e.g. Kevlar, Nomex, etc.) in ballistic vests that are designed to provide ballistic protection that inherently reduced heat transfer. The further increase in R_t from E3 (baseline-without ballistic vest) to E6 was caused by the added layers of turnout suits. Each layer of station uniform and turnout suit trapped more air (which has low thermal conductivity), thereby increased thermal insulation in E3. The additional layer of ballistic vest in E4, E5, and

E6 further increased the thermal insulation. Despite adding hard plates to the ballistic vest in E6, it had a R_t of 0.631 m 2 $\cdot$°C$\cdot$W^{-1} which is lower than E5 (0.652 m 2 $\cdot$°C$\cdot$W^{-1} without hard plates). It suggested that adding hard plates may have reduced air gaps and created more contact points for heat transfer which led to the lowering of thermal insulation of E6.

For whole ensembles, significant increase was observed after turnout suit was added. But adding ballistic vest did not increase the R_t significantly for either the station uniform or the turnout suits. The takeaways from this data are: 1. Ballistic vests added significant thermal resistance when worn over station uniform; 2. Turnout suit was the dominant contributor to heat insulation, once a turnout suit was worn in addition to ballistic vests, its impact was relatively less; 3. No significant difference was found between overt and covert vest wear; 4. Even adding heavy ballistic plates did make no difference (at least in thermal resistance), though weight may impact when considered along with thermal heat loss as contributing to heat strain).

5.1.2 Wet test results (Male manikin)

The evaporative resistance (R_{et}) values for E1, E2, E3, E4, E5, and E6 in the torso area were 0.025, 0.072, 0.09, 0.174, 0.192, and 0.227 m$^2\cdot$kPa$\cdot$W^{-1} respectively (Appendix D). The results indicated that there was a progressive increase in evaporative resistance as more layers of PPE were added.

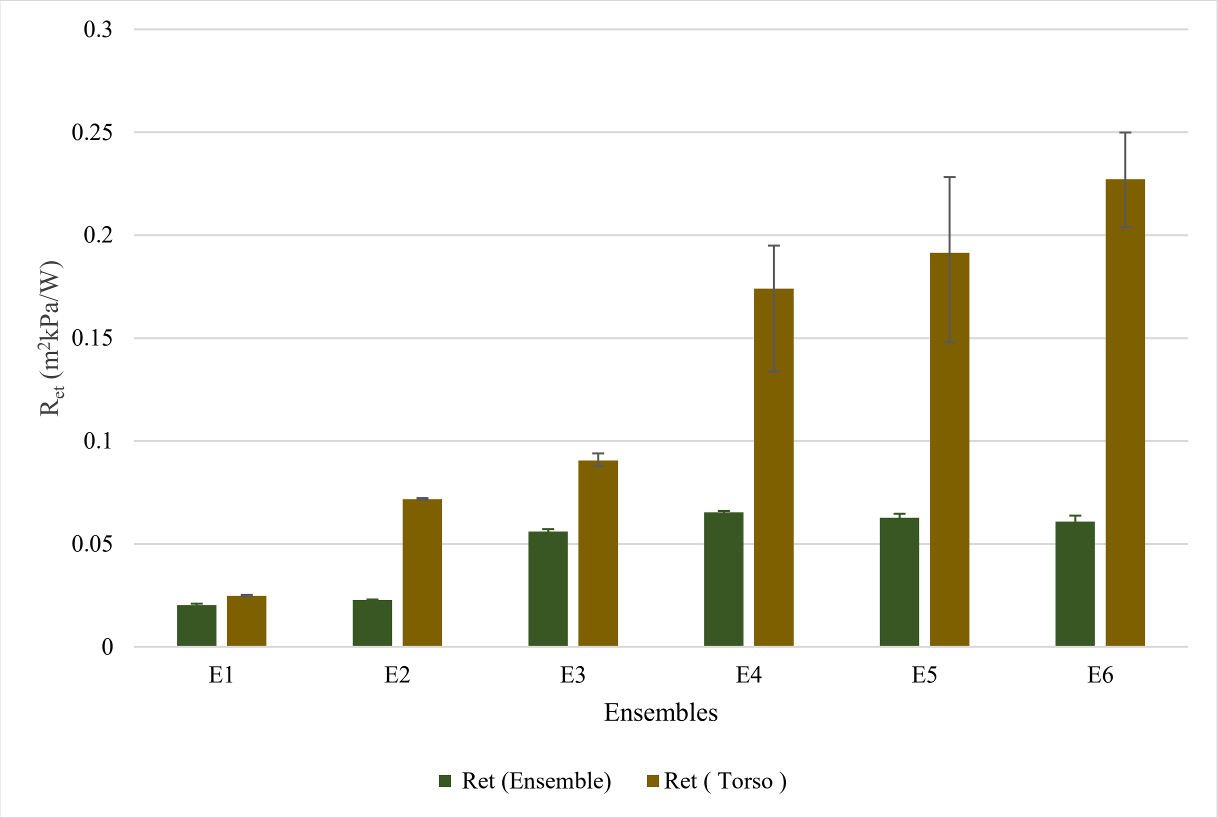


Figure 24. Evaporative resistance of firefighting clothing ensembles in conjunction with ballistic vest on male manikin

On the torso area, E1 (Baseline 1) had the lowest resistance (0.025 $m^2 \cdot kPa/W$), indicating minimal interference with evaporative heat loss. Adding a ballistic vest alone to E1 significantly increased R_{et} (nearly 150%) of E2 compared to E1, showing the vest alone imposes a considerable physiological burden due to its impermeable or semi-permeable materials. E3 (Baseline 2): further increase in R_{et} to 0.090. The turnout suit is known to have low permeability for moisture, which limits sweat evaporation and reduces heat dissipation which aligned with our current findings. E4 had a 100% increase in R_{et} compared to E3. E5 had 113% increase in R_{et} and E6 had 152% increase in R_{et} compared to E3 (baseline 2). The significant increase in evaporative resistance for E6 indicated that the hard plates acted as an impermeable barrier, further restricting moisture vapor transfer.

For whole ensembles, significant increase was observed after the turnout suit was employed. But adding a ballistic vest did not increase the R_{et} significantly for the station uniform and turnout suits.

5.1.3 Predicted total heat loss (Male manikin)

The THL values for E1, E2, E3, E4, E5, and E6 in the torso area were 210.5, 86.9, 66.2, 40, 36.9, and 35.7 W/m^2 respectively (Appendix D). The results showed a decrease of total heat loss in the torso area with the addition of layers.

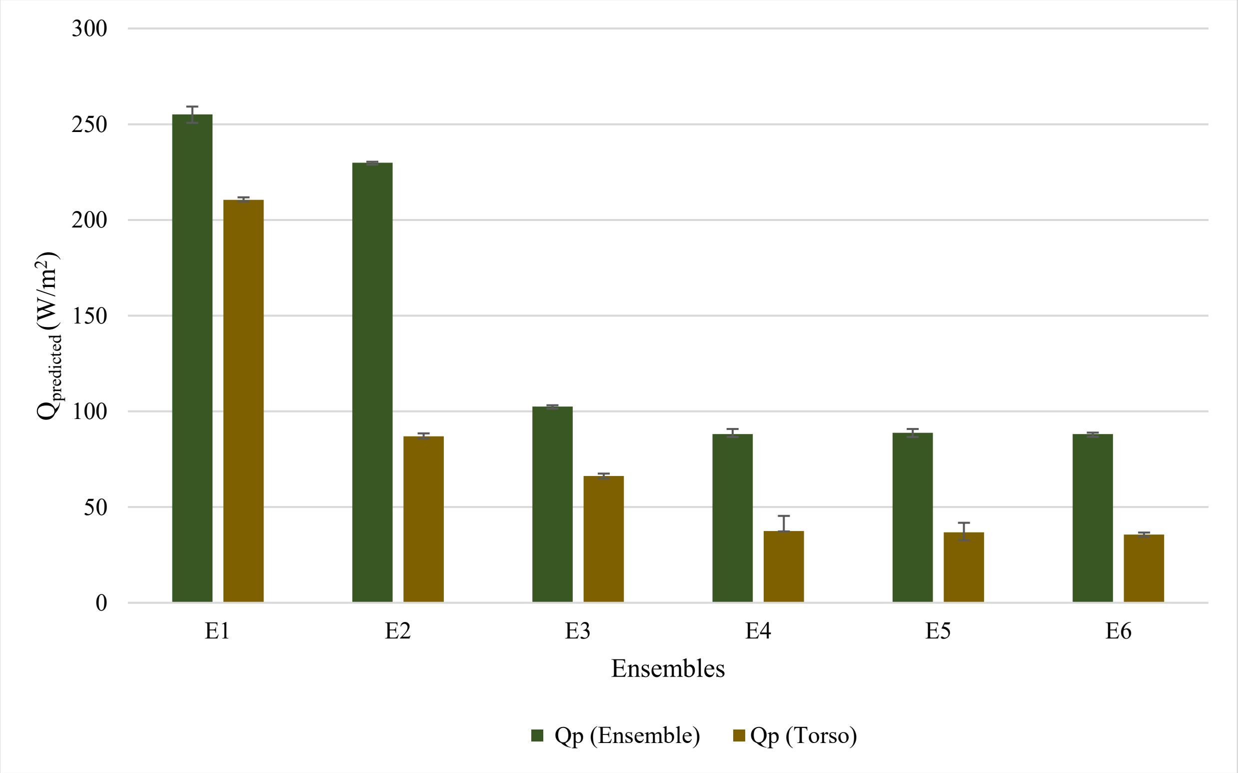


Figure 25. Predicted THL of firefighting clothing ensemble in conjunction with ballistic vest on male manikin

THL decreased from 210.5 w/m^2 in E1 (baseline 1-without ballistic vest) to 86.9 W/m^2 in E2 (with ballistic vest added) representing 58.7% reduction. The substantial decrease in THL from E1 to E2 is due to the dense materials (e.g. Kevlar, Nomex, etc.) in ballistic vests that were designed to provide ballistic protection that inherently reduced heat transfer. The further decrease in THL through E3 to E6 demonstrated the compounding effect of additional layers in the firefighting turnout ensemble with ballistic vests. E3 (Baseline 2) had a THL of 66.2 w/m^2 which means multi-layer construction and low permeability of turnout suit materials made the turnout suit more restrictive for total heat loss compared to the E1 alone and E2. THL decreased by 39.6% compared to baseline 2. THL dropped further to 36.9 for E4, a 44.4% reduction compared to baseline 2. Heat loss reduction between the ballistic vest worn under (E4) and over(E5) the turnout jacket is minor (40.0 → 36.9 W/m^2). It indicated that the ballistic vest material itself, regardless of placement, serves as a significant barrier to heat dissipation. For E6, the reduced THL value is 35.7 W/m^2, a 46.1% reduction from the baseline. It indicated that the presence of hard plates slightly exacerbates the thermal burden by trapping heat closer to the body.

5.1.4 Dry test results (Female manikin)

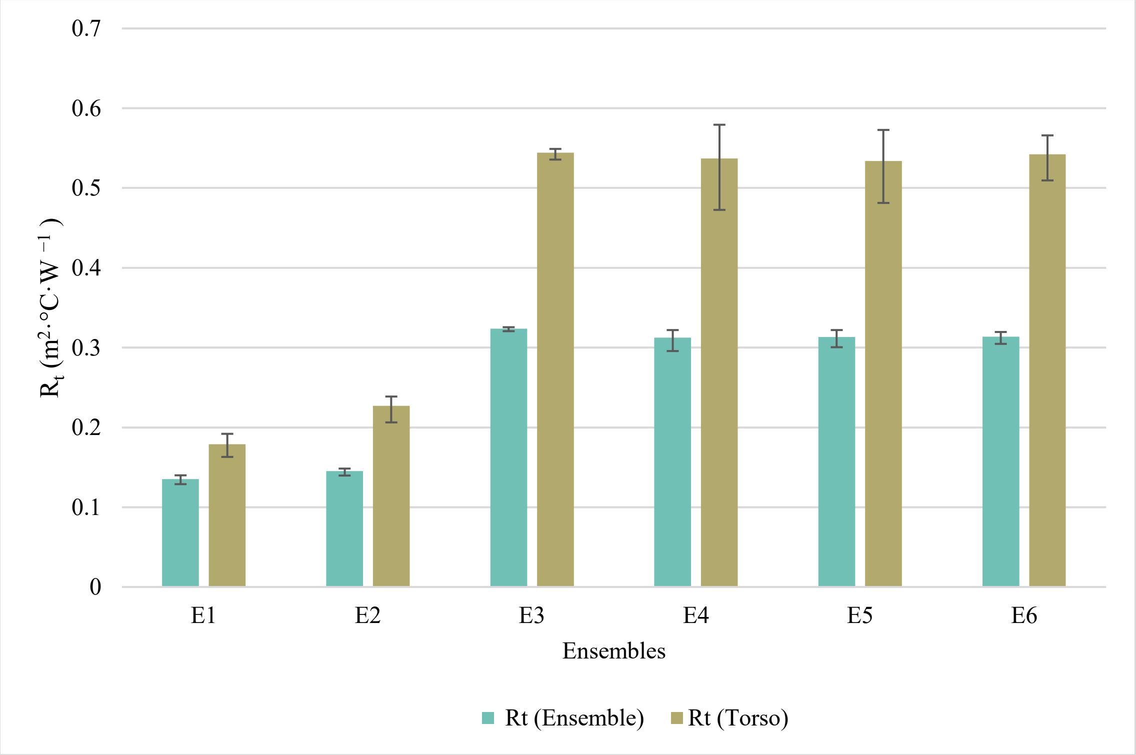


Figure 26. Thermal resistance of firefighting clothing ensembles in conjunction with ballistic vest on female manikin

E1 (baseline 1) showed the lowest R_t (ensemble ≈ 0.13, torso ≈ 0.17), indicating minimal thermal burden. E2 slightly increases both ensemble and torso R_t, reflecting added fabric/layering, but the increase is modest. E3 (baseline 2) showed a major jump in torso insulation (≈ 0.54), while ensemble thermal resistance increased only to ≈ 0.32. This suggested that additional protective elements (likely ballistic or layered inserts) concentrated thermal resistance over the torso rather than uniformly across the body. From E3 through E6, ensemble R_t remained nearly stable (≈ 0.31–0.32), indicating that additional gear did not substantially increase whole ensemble R_t. In contrast, torso R_t remained consistently high (~0.53–0.55), meaning the torso continued to bear the greatest thermal load despite no further ensemble-level increase. This plateau effect highlighted a localized insulation bottleneck at the torso. Across all ensembles, torso R_t was consistently higher than ensemble R_t, confirming that torso R_t was disproportionately greater. The torso-to-ensemble difference was small in E1–E2 but became large in E3-E6 (≈ 0.20–0.22 difference), showing that the torso is the most thermally insulated region when turnout gear and ballistic protective systems were added.

5.1.5 Wet test results (Female manikin)

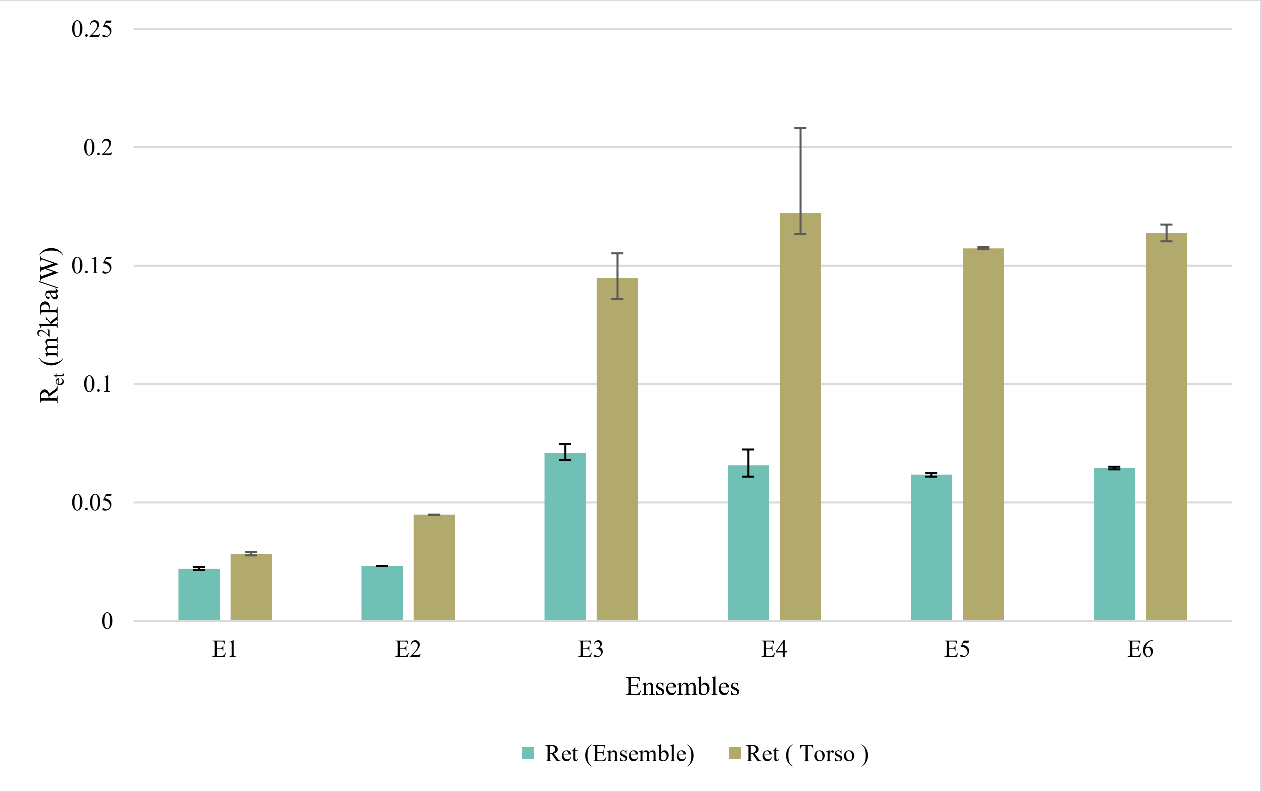


Figure 27. Evaporative resistance of firefighting clothing ensembles in conjunction with ballistic vest on female manikin

In Figure 26, E1 showed the lowest evaporative resistance for both ensemble and torso (~0.02-0.025 m²kPa/W), suggesting minimal interference with evaporative cooling. Adding a ballistic vest to station uniform (E2) slightly increased R_{et}, particularly in the torso (≈0.045). This indicated that even lightweight protective layers noticeably restrict torso evaporative heat loss compared to the rest of the body. E3 shows a marked rise in torso R_{et} (~0.145) compared to ensemble (~0.07). This demonstrated that torso evaporative resistance doubles relative to the ensemble average, highlighting how concentrated protective layering over the torso impeded sweat evaporation from this critical region. For E4 & E5, ensemble R_{et} stabilized around 0.06-0.07, but torso R_{et} remained disproportionately higher (~0.16-0.18). The error bar for covert was wider, suggesting greater variability in torso evaporative resistance possibly due to fit, fabric overlap, or variability in garment coverage. E6 showed values similar to Overt, again with torso R_{et} (~0.165) much higher than ensemble R_{et} (~0.065).

In summary, the data revealed that torso evaporative resistance dominated thermal burden, consistently being two to three times higher than ensemble-level values. While whole-body averaged plateau across protective ensembles, torso values remained elevated, showing that the torso was the critical limiting factor for evaporative cooling.

5.1.6 Predicted total heat loss (Female manikin)

Figure 28 presented the predicted total heat loss ($Q_{predicted}$) for the female manikin across the six ensembles (E1–E6), reported separately for the whole ensemble and the torso region. $Q_{predicted}$ represented the maximum cooling potential, with higher values indicating greater capacity for heat dissipation.

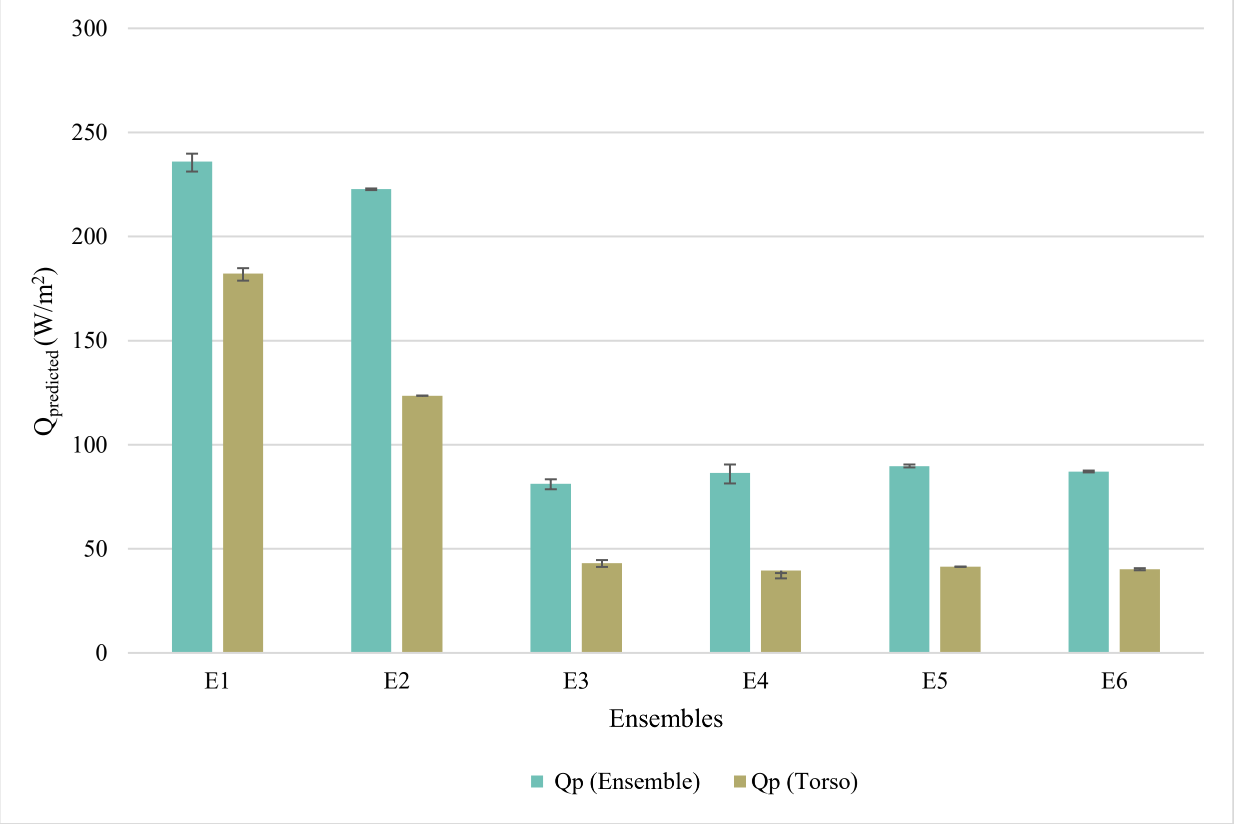


Figure 28. Predicted THL of firefighting clothing ensemble in conjunction with ballistic vest on female manikin

The station uniform provided the highest predicted total heat loss among all ensembles. Whole ensemble heat loss reached ~235 W/m², while torso values were lower, ~180 W/m². This indicated that even under minimal layering, the torso contributed disproportionately to limiting evaporative heat loss. This disparity reflected the torso's larger evaporative resistance, where garment coverage and fabric density directly reduced the effectiveness of sweat vapor transfer compared to more exposed regions such as the arms and legs.

Adding a ballistic vest (E2) produced a marked reduction in predicted total heat loss (when worn only over a station uniform). Whole-body values dropped to ~220 W/m², and torso values decreased sharply to ~120 W/m². The torso-specific decline highlighted the significant evaporative burden imposed by the vest, which introduced rigid, multilayered fabric structures over the chest and back. The difference between ensemble and torso values widened compared to E1, underscoring how the torso became the critical limiting region once ballistic protection is incorporated.

The greatest reduction in predicted total heat loss occurred in ensemble E3, where a station uniform was combined with turnout gear. Whole-body heat loss fell to ~80 W/m², and torso values dropped below ~45 W/m². This decline demonstrated that the dominating effect of the turnout suit nearly eliminated the torso's ability to support effective evaporative cooling. The female manikin's torso anatomy, with greater curvature in the chest and hip regions, likely exacerbated localized fit issues, further reducing ventilation and increasing vapor entrapment.

For ensembles E3-E6, whole-body predicted total heat loss stabilized between ~85-90 W/m², with torso values consistently ~40 W/m². These values remained low and relatively uniform across vest positioning, indicating that once multiple and multilayered barriers of turnout suits were introduced, the addition and position of ballistic vest had limited additional impact on evaporative cooling potential.

5.1.7 Male vs female thermal resistance

Thermal resistance (R_t) or insulation is a net effect of clothing coverage, fit, and air gaps [181]. If the vest does not adequately conform to the female form, the combination of poor coverage and air leakage can reduce R_t. Male manikins typically have a broader torso with a flatter chest, allowing the ballistic vest and T-shirt to fit more snugly and provide greater torso coverage. In Figure 29, the torso thermal resistance (R_t) values revealed consistent yet ensemble-dependent differences between the male and female manikins, underscoring the influence of body shape and garment fit on insulation properties. Across all six ensembles, both manikins demonstrated the expected rise in R_t with the addition of ballistic protection; however, the magnitude and direction of gender-specific differences varied with ensemble design.

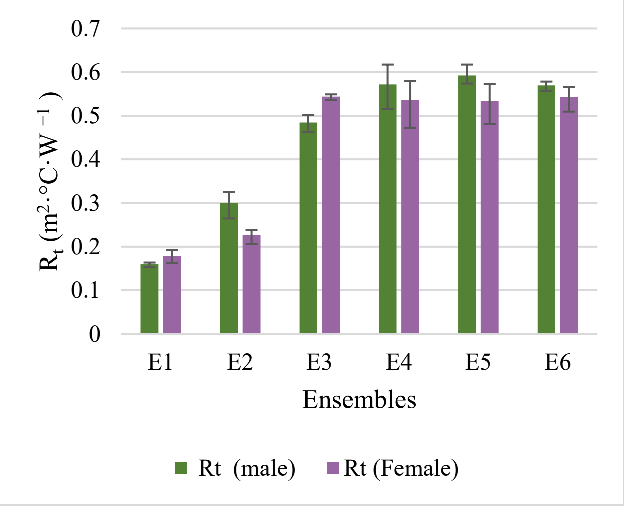


Figure 29. Male vs female torso R_t

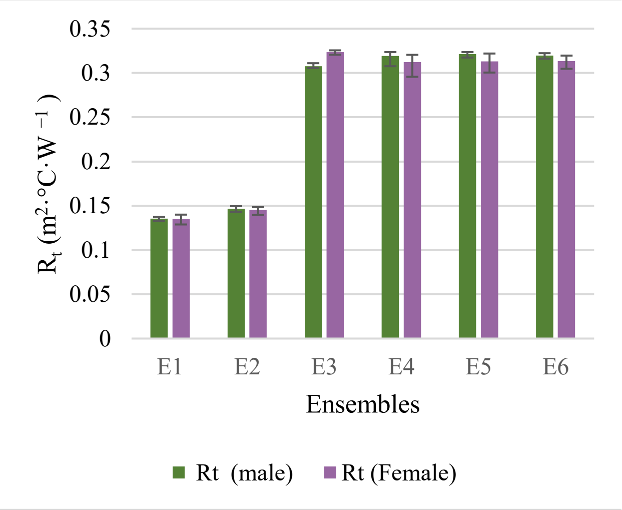


Figure 30. Male vs female whole ensemble R_t

On the torso area (Figure 29), the most significant differences were observed when a ballistic vest was donned (E1 vs E2). Baseline ensembles (E1 & E3) showed higher R_t in female. Female anatomy by default has more curvature and air gaps. Therefore, after adding ballistic vests, the air gap reduced and the R_t decreased in female torso compared to non-ballistic vest ensembles on the female manikin. Largest overall factor in increasing thermal resistance was the turnout suit (much more significant than vest). Once turnout suit was donned, relatively little difference was observed related to clothing configurations (wearing vest over or under suit). Even adding a vest with hard plates did not contribute to major differences in R_t.

For the station uniform alone (E1), the female manikin showed slightly higher R_t than the male manikin. This was attributable to the smaller torso circumference and more contoured chest shape of the female manikin, which promoted closer garment-to-skin contact and reduced ventilation gaps, thereby limiting convective heat loss. In contrast, the male's broader and flatter chest created small stagnant air layers between fabric and skin by reducing direct conduction and overall lowering the insulation effect.

When the ballistic vest was added to the station uniform (E2), male R_t exceeded female values. The ballistic vest is designed primarily for male anatomy which may leave more of the female torso (especially the chest area) uncovered. This exposes the breast region to more direct heat loss from the side, especially through radiation and convection, reducing insulation. Female manikins may have less continuous contact points due to curvature variations, leading to marginally better heat dissipation due to less coverage (more exposed areas) that facilitates more air movement or convective heat loss. This difference highlights how vest geometry interacts with torso shape to modulate thermal resistance. These effects, however, may also be artificial and the manikin surface is non-deformable, whereas human breast tissue may experience significant compression, further reducing wear comfort, besides effects on overall insulation.

The addition of the turnout suit to station uniform (E3) further amplified R_t for both genders, but the female manikin showed slightly higher R_t. The bulk of the turnout system introduced multiple layers of entrapped air, and on the female torso, reduced garment compression maintained these insulating layers more effectively. The male torso, with greater breadth, may have compressed the turnout system more, slightly reducing trapped air volume.

For the covert vest (E4), torso thermal resistance (R_t) was higher in the male than in the female manikin (≈ 0.58 vs. ≈ 0.52 $m^2 \cdot °C \cdot W^{-1}$, with limited error-bar overlap). This reflected how a smooth, body conforming carrier interacted with torso geometry. On the male's flatter, broader chest, the covert vest fitted more uniformly and compresses the layers underneath, creating well-sealed air layers that restricted convective exchange and elevate R_t. In contrast, the female torso curvature and stronger bust-to-waist taper tended to leave narrow, connected air gaps near the lateral chest, under-bust region, and along the armhole/neck edges. These gaps may have formed continuous vertical pathways that potentially allowed natural convective heat loss. Even though the vest locally compressed over the bust, the presence of these connected pathways created sensible heat transfer, yielding a lower R_t for the female. Thus, with the covert ensemble predominated on the male R_t compared to female torso.

For the overt vest (E5), the difference in torso thermal resistance (R_t) could be explained by how the vest fitted each body shape. On the male torso, a flatter and more uniform chest allowed the vest panels to fit evenly and maintain continuous contact, compressing underlying layers and sealing the torso microclimate which limited internal air movement and yielded higher R_t. On the female torso, the bust and waist curvature made the same vest pattern more likely to bridge over curved regions and lose full contact along the lateral chest, under-bust, and near armhole/neck edges. These geometry-driven gaps form connected pathways from lower to upper edges, enabling modest vertical movement of warm air and localized micro-ventilation and therefore reduced R_t compared to the male torso in E5.

Finally, the vest with hard plates (E6) showed minimal gender-based differences, with nearly overlapping values. The rigidity of the plates reduced the influence of torso shape by forcing close garment contact and minimizing the role of trapped air, thereby equalizing insulation effects between the two manikins.

Collectively, these findings showed that anatomical differences in torso shape particularly chest curvature, torso circumference, and breadth that may have directly affected how garments and ballistic vests fitted and consequently how air layers were formed or compressed. Female manikins generally showed higher R_t when ensembles were form-fitting

(E1 and E3), while males exhibited higher values when vest design was looser or bulkier (E2, and E4-E6). These nuances are crucial for understanding thermal burden in operational contexts, as even modest differences in torso R_t can significantly influence thermoregulation and heat stress risk during firefighting or tactical operations.

In Figure 30, thermal resistance (R_t) for whole-ensembles were shown. R_t values for the station uniform (E1) were lowest for both manikins compared to other ensembles, as expected given the lightweight single-layer design. The female manikin demonstrated a slightly higher R_t, likely due to closer garment conformity to a narrower torso and hip structure, which reduced air circulation and convective losses. In contrast, the broader male body shape allowed for small ventilation gaps, lowering insulation.

The addition of a ballistic vest to the station uniform (E2) increased thermal resistance modestly for both manikins. Values remained closely aligned, but the male manikin showed a small relative increase. This suggests that the vest span across the male's wider torso, entrapping more stagnant air, while fitting more snugly against the female's curved chest profile, thereby reducing the opportunity for insulating air pockets.

With the station uniform and turnout suit combination (E3), a substantial increase in R_t was observed. The female manikin exhibited marginally higher resistance, consistent with reduced compression of multilayered garments over a curved and smaller torso circumference, preserving thicker air layers. The male manikin's flatter chest likely trapped less air layers, slightly diminishing R_t.

For the covert (E4), overt (E5), and hard plates (E6), male and female manikins showed similar patterns where male thermal resistance were slightly higher than female with minimal gender-based differences. This pattern was identical to the torso data for the whole ensembles. In

E6, male and female showed very negligible differences compared to E4 and E5 indicating the rigidity of the plates reduced the importance of anatomical contours by enforcing a uniform garment-body interface, thereby equalizing thermal resistance.

In summary, the whole-ensemble results showed that female manikins demonstrated slightly higher or similar thermal resistance when ensembles were without ballistic vest and less compressed (E1, and E3), whereas male manikins exhibited higher or comparable resistance when vests were bulkier or less fitted (E2, E5). The overall increase in R_t with ballistic protection underscores the additional thermal burden imposed by these systems, which has direct implications for heat dissipation and thermoregulation during high-exertion tasks.

5.1.7.1 Statistical analysis of thermal resistance

One-way ANOVA test (one-way analysis of R_t by gender) was run to identify if there are significant differences between males and females in thermal resistance both for torso area only and whole ensemble.

Table 5. Thermal resistance test results in the torso area and whole ensemble

	Torso		**Ensemble**	
	R_t (male)	R_t (Female)	R_t (male)	R_t (Female)
	0.154	0.163	0.1326	0.1289
E1	0.161	0.182	0.136	0.1365
	0.164	0.192	0.1374	0.14
	0.265	0.237	0.148	0.1484
E2	0.308	0.206	0.1495	0.1397
	0.326	0.239	0.143	0.148
	0.463	0.536	0.3064	0.3206
E3	0.488	0.548	0.3111	0.3249
	0.502	0.549	0.3056	0.3256
	0.515	0.552	0.3077	0.3161
E4	0.563	0.473	0.3219	0.2957

Table 6. (continued)

	Torso		Ensemble	
	R_t (male)	R_t (Female)	R_t (male)	R_t (Female)
	0.578	0.579	0.3214	0.3205
	0.574	0.481	0.3174	0.3005
E5	0.617	0.547	0.3228	0.3173
	0.587	0.573	0.3237	0.322
	0.557	0.510	0.3201	0.3047
E6	0.578	0.552	0.3224	0.3164
	0.574	0.566	0.3161	0.3196
F(1, 29)	1.7739		0.1512	
p	0.1933		0.7003	

The ANOVA test results for the torso area indicated that the main effect of gender on thermal resistance (R_t) was not statistically significant *(F(1, 29) = 1.7739, p = 0.1933)*. When R_t values were averaged across all ensemble configurations, no significant overall difference was observed between male and female manikins. This finding suggested that gender, considered as an isolated factor, did not exert a uniform influence on whole-ensemble thermal resistance. Instead, the magnitude of insulation appeared to be predominantly governed by ensemble design and material composition, rather than by gender alone. These results indicate that thermal performance differences between male and female manikins were better interpreted as configuration-specific responses rather than as a uniform gender effect.

The ANOVA test results for whole ensemble showed that the main effect of gender on thermal resistance (R_t) was not statistically significant *(F(1, 29) = 0.1512, p = 0.7003)*. When R_t values were averaged across all ensemble configurations, no meaningful difference was observed between male and female manikins, indicating that gender alone did not systematically influence whole-ensemble thermal resistance. This result reinforces the conclusion that thermal insulation at the ensemble level was driven predominantly by garment system design, materials, and layering, rather than by gender as an independent explanatory factor. Consequently, any observed gender-related differences in thermal performance were more appropriately interpreted within the context of specific ensemble configurations and garment-body interactions, rather than as a uniform effect of gender.

5.1.8 Male vs female evaporative resistance

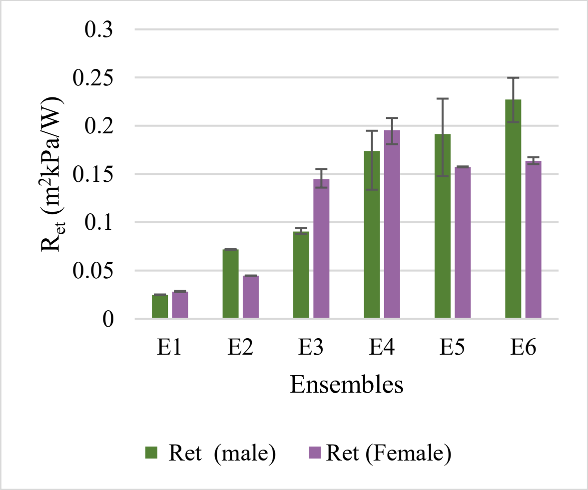


Figure 31. Male vs female torso R_{et}

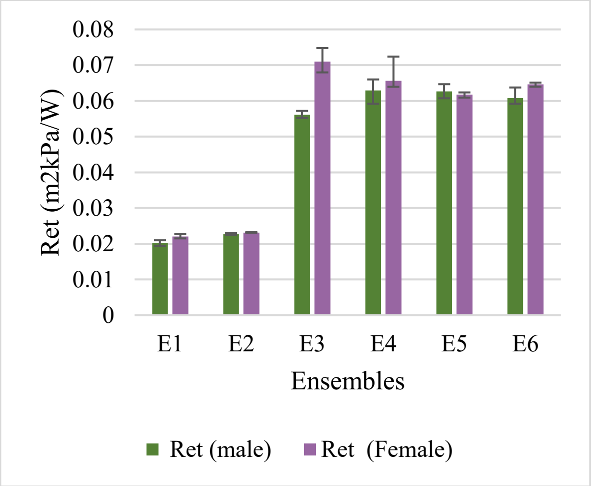


Figure 32. Male vs female whole ensemble R_{et}

Figure 31 exhibited the evaporative resistance (R_{et}) of six ensembles (E1-E6), with a focus on the torso region where both evaporative cooling and garment fit play critical roles. R_{et} quantifies the resistance to sweat vapor transfer across clothing and thus reflects the ability of the body to dissipate heat via evaporation.

In the station uniform (E1), R_{et} was minimal (~0.02-0.03 m²kPa/W) and male-female values were very close, indicating that with thin, compliant fabrics the torso microclimate remained well-ventilated and anatomical differences exerted little influence on vapor diffusion.

Adding a ballistic vest to the station uniform (E2) increased R_{et} for both manikins, but female R_{et} is notably lower than male (≈0.05 vs. ≈0.08 m^2kPa/W). This reversal was consistent with a vest-bridging/edge-gap mechanism on the female torso: bust curvature may have forced the vest to span the chest, opening armhole/neck/side leak paths that ventilated the vapor in upper-torso zones. On the male's flatter chest, the vest fitted more uniformly, potentially producing fewer through-flows and a thicker mass-transfer boundary layer resulting in higher $R_{et.}$

With the turnout suit layered over the station uniform (E3), R_{et} increased sharply for both manikins (≈0.10-0.15 m^2kPa/W), and the female exceeded the male (female ≈0.14, male ≈0.10). Here the bulky outer shell of the turnout suit may have restricted the edge leaks while curvature and compression under the suit created stagnant, humid pockets (under-bust, mid-sternum) that lengthened vapor path and elevated R_{et}. In the covert ensemble (E4), both manikins showed further elevation (≈0.18-0.20 m^2kPa/W), with the female slightly higher. The possible reason may be the male cut ballistic vest not fitting properly to the female contour causing more vapor trapped under the turnout suit leading to a higher R_{et} whereas male had a flatter torso and uniformly fitted ballistic vest under the turnout suit leaving less air gaps or vapor trapped in the torso area.

The overt ensemble (E5) showed female R_{et} was lower than male (≈0.16 vs. ≈0.19 m^2kPa/W). When combined with the female torso's bust-to-waist contour, the vest design promoted air movement and facilitates the removal of warm, humid air from the central chest region. In contrast, the male torso's more uniform geometry results in closer and more continuous contact with the ballistic vest, reducing pressure differences and allowing a more saturated microclimate to persist. The hard-plate ensemble system (E6) amplified this effect where rigid plates imposed and created continuous vertical gaps that the female geometry leveraged more effectively, yielding female R_{et} ≈0.16 vs. male ≈0.22-0.24 m²kPa/W.

Across all ensembles, R_{et} increased in proportion to garment bulk and structural rigidity, reflecting the trade-off between ballistic protection and evaporative heat loss. However, the torso region emerged as a critical site where body shape strongly impacted outcomes. The female manikin's torso curvature led to greater evaporative resistance in layered or rigid ensembles (E3 & E4), whereas the male torso allowed garments to fit more uniformly and maintain slightly better vapor transfer. The elevated torso R_{et} observed in female manikins indicated that standardized gear, often designed around male anthropometry, may disproportionately impede evaporative cooling in female firefighters. Such limitations directly increased the risk of uncompensated heat storage and heat strain during operational scenarios.

Figure 32 depicted the evaporative resistance (R_{et}) of six whole ensembles (E1-E6) for male and female thermal manikins. R_{et} provided a measure of the resistance to sweat vapor transfer across the clothing system and is therefore an essential indicator of the ensemble's capacity to allow evaporative heat loss. The station uniform (E1) produced the lowest R_{et} values (~0.02 m²kPa/W) for both manikins, with slightly higher R_{et} values for the female. When a ballistic vest was added to the station uniform (E2), R_{et} increased slightly but remained low, showing minimal variation between male and female. These findings suggested that in the absence of bulky or rigid layers, torso fit, and anatomical differences exerted little influence on vapor permeability.

The most notable gender-based difference occurred in ensemble E3, where the station uniform was combined with the turnout suit. R_{et} increased sharply for both manikins, but values were substantially higher in the female (~0.071 m²kPa/W) than the male (~0.056 m²kPa/W). This

25-30% elevation can be linked to torso-specific anatomical features: the female manikin's pronounced chest curvature and narrower waist likely disrupted garment conformity, producing microclimate zones of trapped air in the upper torso and chest. These stagnant regions would inhibit vapor transport, leading to higher measured R_{et}. The straighter and broader male torso provided a more uniform contact surface, reducing vapor entrapment and resulting in lower R_{et} values.

Ensembles E4-E6 consistently exhibited elevated R_{et} (~0.06–0.07 m^2kPa/W). While male and female values were closely aligned, females generally retained slightly higher R_{et}, particularly with the covert (E4) and hard plate vest (E6). In E6, the rigid torso plates likely interacted with the female chest and waist contours creating additional areas of restricted airflow and vapor stagnation. In the whole ensemble level, only overt (E5) showed lower R_{et} for female, otherwise all the ensembles showed either similar (E2) or higher (E1, E3, E4, & E6) R_{et} for female compared to male.

Across all ensembles, R_{et} increased with garment layering and protective bulk. The finding that female manikins exhibit higher R_{et} values in specific ensembles emphasizes the influence of anatomical differences and garment fit on thermal performance. While the absolute differences between genders were smaller at the whole-body level than at the torso, the consistent trend of elevated R_{et} in females raises concerns about gender-specific vulnerability to heat strain. Design modifications that improve garment fit across diverse body shapes, particularly in layered configuration and may be critical in reducing heat strain risk for all firefighters.

5.8.1.1 Statistical analysis of evaporative resistance

One-way ANOVA test (One-way analysis of R_{et} by gender) was run to identify if there are significant differences between males and females in evaporative resistance both for torso area only and whole ensemble.

Table 7. Evaporative resistance test results in the torso area and the whole ensemble

	Torso		**Ensemble**	
	R_{et} (male)	R_{et} (Female)	R_{et} (male)	R_{et} (Female)
	0.0244	0.029	0.0194	0.0226
E1	0.0252	0.0279	0.0209	0.0218
	0.0247	0.0276	0.0203	0.0215
	0.0722	0.0448	0.0226	0.0232
E2	0.0715	0.0447	0.0224	0.0231
	0.0715	0.0448	0.0230	0.0231
	0.0939	0.1552	0.0571	0.0747
E3	0.0877	0.1432	0.0558	0.0702
	0.0898	0.1360	0.0551	0.0679
	0.1338	0.1971	0.0646	0.0723
E4	0.1949	0.2081	0.0654	0.0719
	0.1932	0.1809	0.0660	0.0673
	0.1984	0.1569	0.0625	0.0623
E5	0.2282	0.1579	0.0646	0.0618
	0.1478	0.1569	0.0607	0.0609
	0.2038	0.1603	0.0591	0.0651
E6	0.2279	0.1674	0.0594	0.0649
	0.2498	0.1637	0.0637	0.0639
F(1, 29)	0.7166		14.9338	
p	0.4042		0.0006 <0.001	

The ANOVA test results for torso area only indicated that the main effect of gender on evaporative resistance (R_{et}) was not statistically significant *(F(1, 29) = 0.7166, p = 0.4042).*

When R_{et} values were averaged across all ensemble configurations, no significant difference was observed between male and female manikins on the torso area, indicating that gender, when considered as an independent factor, did not exert a consistent influence on torso-level evaporative resistance. This finding suggested that evaporative heat transfer at the torso may not have uniformly governed by gender alone, but was instead primarily shaped by ensemble characteristics, with any gender-related differences likely arising from ensemble-specific garment-body interactions rather than as a main effect.

The ANOVA test results for the whole ensemble revealed a statistically significant main effect of gender on evaporative resistance (R_{et}) $F(1, 29) = 14.9338, p= 0.0006 < 0.001)$. When R_{et} values were averaged across all ensemble configurations, female manikins consistently exhibited higher evaporative resistance than male manikins, indicating a systematic difference in whole-ensemble insulation between genders. This finding suggested that gender-associated differences in garment fit, air-gap distribution, and garment-body interactions contribute meaningfully to evaporative resistance, even when the ensemble configuration is held constant.

The absence of a statistically significant gender effect in torso-level evaporative resistance (R_{et}), despite a significant gender effect at the whole-ensemble level, may have reflected fundamental differences in the dominant heat and moisture transfer mechanisms operating at local versus global scales. At the torso, evaporative performance may have largely governed by garment structure rather than body morphology. The presence of rigid or semi-rigid elements, multilayer assemblies, and high material coverage by ballistic vests in the torso region suppressed airflow and vapor diffusion pathways for both male and female manikins. Under these conditions, evaporative resistance may primarily depend on material properties, layer thickness, and permeability, effectively constraining the influence of gender-specific anatomical differences. As a result, male and female torso R_{et} values converge, yielding no statistically detectable gender effect at the torso area.

In contrast, whole-ensemble evaporative resistance integrated the contributions of multiple body regions beyond the core torso, including the shoulders, arms, lateral torso margins, hips, and lower body. These regions were typically less constrained by rigid protective elements and were therefore more sensitive to differences in garment fit, drape, and air-layer formation. Female anthropometry characterized by greater waist taper, increased curvature, and non-uniform body contours may have tended to produce heterogeneous air layers and altered vapor boundary layers in these peripheral regions. When evaporative resistance was averaged across the entire body surface, these region-specific differences accumulate, resulting in a statistically significant main effect of gender at the whole-ensemble scale.

Additionally, whole-ensemble R_{et} was inherently influenced by surface area weighting across body segments. Newton’s larger total surface area and more uniform garment contact facilitate distributed evaporation across multiple regions, whereas Liz’s smaller surface area combined with heterogeneous air-gap distributions increases effective vapor resistance when averaged across the body. These surface-area and weight effects exerted minimal influence when evaluating the torso alone but became increasingly important in whole-ensemble assessments, thereby contributing to the emergence of a significant gender effect.

5.1.9 Male vs female torso analysis

The male having comparatively higher (slightly) thermal and evaporative resistance than female while wearing the vest was unexpected. Due to the curvature of the chest and the vest covering more surface area of the female torso, it was assumed that both resistance values would be higher in the female, as trapped air usually results in higher resistance values. When observing both manikins dressed in the vest (Fig. 33), the female manikin's hard curves (chest and lower back) in the torso created non-uniform contact between the vest and torso that produced ventilation channels instead of trapped air that could enhance heat and vapor movement, hence, producing lower R_t and R_{et}. The male manikin, on the other hand, had much flatter surfaces which allowed a very snug fit and fewer areas for ventilation channels.

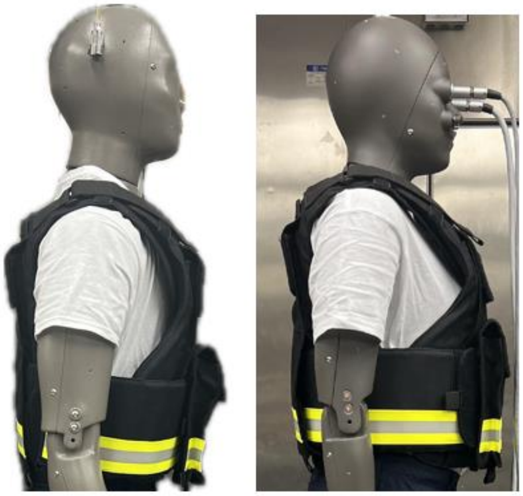


Figure 33. Male (left) vs female (right) torso coverage

Overall, none of the whole ensembles showed any significant differences in R_t and R_{et}, between male and female. However, the torso area showed interesting results in terms of higher and lower R_t and R_{et} pattern in males and females. To better understand why adding the vest increases the thermal and evaporative resistance on the male and female manikins in a more pronounced way, a visual assessment of each zone in the torso was conducted.

These diagrams illustrated thermal and evaporative resistance across the torso area of male and female manikins wearing firefighting suits with and without ballistic vests. Color coding provided a clear visual representation of the magnitude of thermal burden, with deep blue indicating low values and shades of purple to red signifying progressively higher levels of thermal and evaporative resistance. In Figures 34-45, the left two images represented the front and back of the male manikin torso, which were divided into six zones. The right two images represented the front and back of the female manikin torso, which were divided into only four zones. The number of zones was set by the manikin manufacturer.

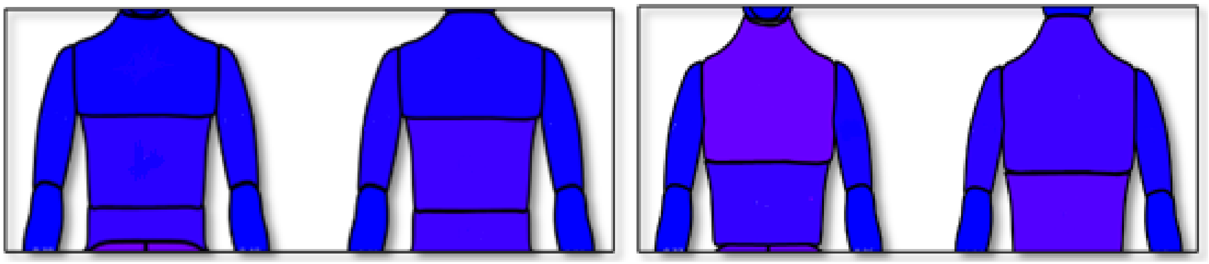


Figure 34. Thermal insulation of station uniform (SU) on male front/back (left) and female front/back (right)

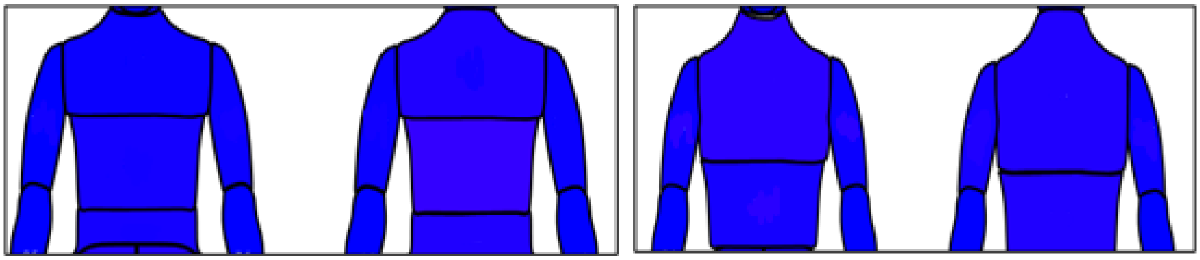


Figure 35. Evaporative resistance of SU on male front/back (left) and female front/back (right)

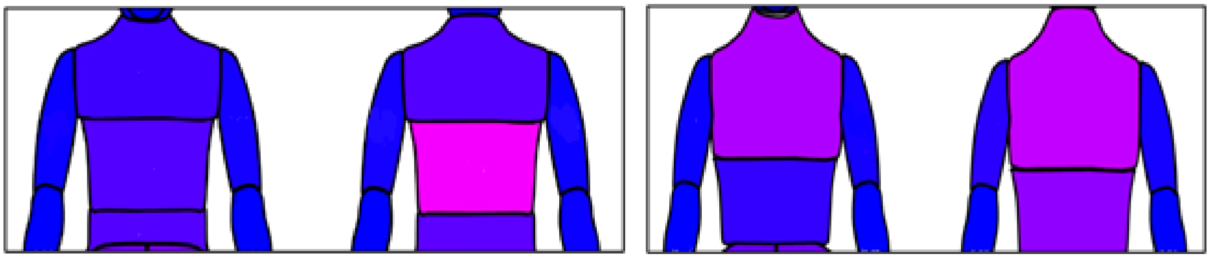


Figure 36. Thermal insulation of station uniform with vest (SUV) on male front/back (left) and female front/back (right)

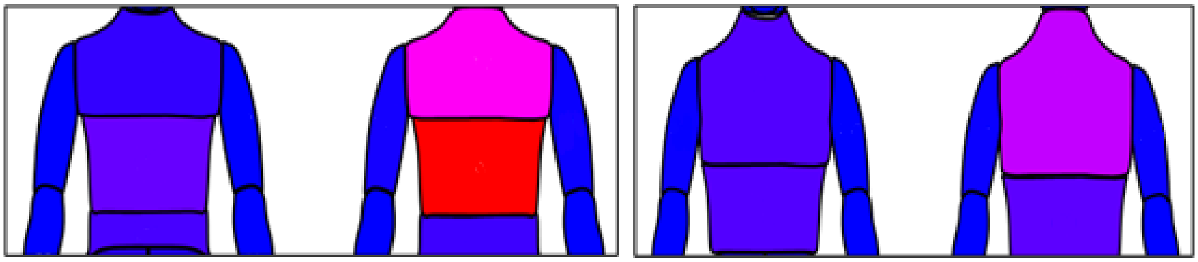


Figure 37. Evaporative resistance of SUV on male front/back (left) and female front/back (right)

Figure 34 showed that the male manikin (left) had similar thermal resistance (R_t) all over the torso (uniform blue color), whereas the female manikin had slightly higher R_t & R_{et} in the chest and lower back (right). This very slight increase was attributed to air gaps created from the hard contours of the breast and lower back, and the additional layer of athletic bra. Figure 36 depicted that the addition of a ballistic vest (SUV) markedly increased thermal resistance in both male and female manikins, as evidenced by the transition from predominantly blue hues in SU ensembles (Figure 34) to pink/purple regions in SUV (Figure 36), particularly in the central torso. The female showed a purple tint in the chest, shoulder, and lower back, while the male only showed a pink tint on the midback area. Nevertheless, this one area produced such a high R_t value that when averaged, the male torso R_t exceeded the female torso R_t when a ballistic vest was added to the station uniform. This value was high because the ballistic vest mostly covered the male torso area (>90%), and it fit snugly to the area of the manikin. This left only one path for the heat to leave the system, and that was through the vest, which is difficult to dissipate. The hard curvatures in the female may have created better ventilation paths between the breasts, armpits, and out the curved lower back.

Figure 35 showed the evaporative resistance (R_{et}) of male and female manikins in station uniform in the torso area where there were no observed hue differences. However, after adding the ballistic vest to the station uniform, evaporative resistance elevated significantly over the central torso (Figure 37). The red region in the male SUV back (Figure 37/left) indicated an extreme barrier to evaporative cooling, highlighting a critical zone of potential heat retention. The female manikin had higher R_{et} in the shoulder and midback areas (Figure 37/right); however, the increase was not large enough to eclipse the overall male torso R_t value. Anatomical differences such as breast contours, torso curvature, and overall body shape likely contributed to this disparity, as they could lead to altered garment fit and increase ventilation in female configurations. Overall, the data underscored the thermal and evaporative burden imposed by ballistic vests, with elevated risks in key torso regions, especially the back and chest, thereby raising concerns about thermoregulation and heat stress during firefighting duties.

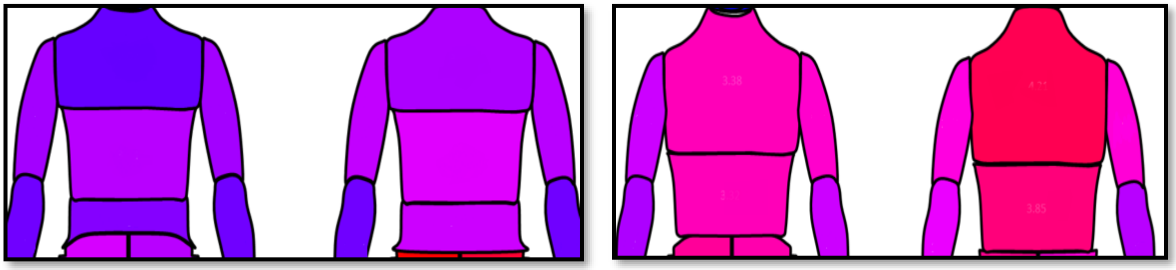


Figure 38. Thermal insulation of turnout suit (TS) on male front/back (left) and female front/back (right)

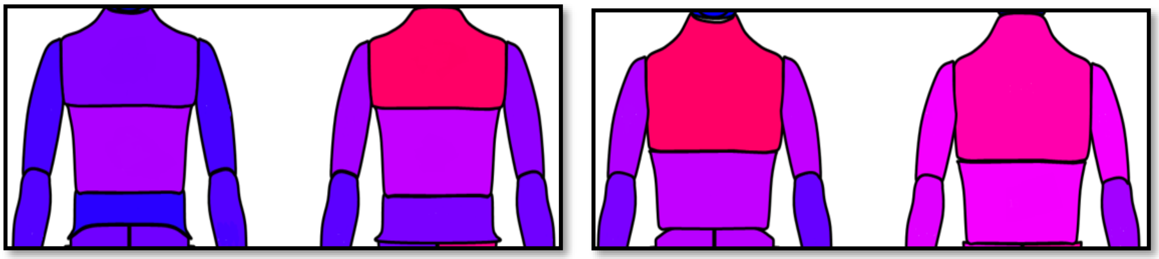


Figure 39. Evaporative resistance of TS on male front/back (left) and female front/back (right)

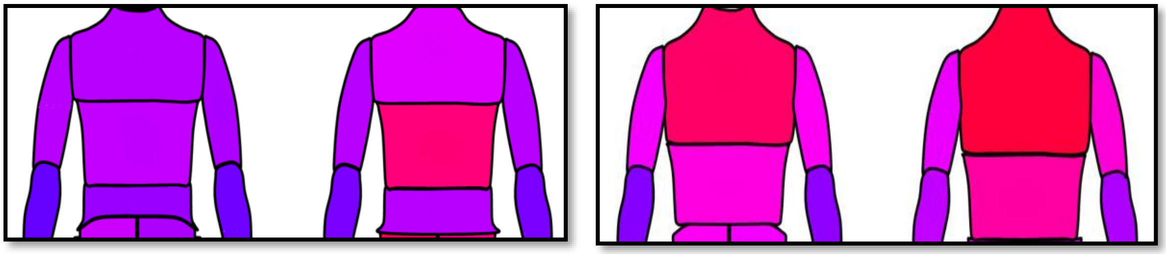


Figure 40. Thermal insulation of Covert on male front/back (left) and female front/back (right)

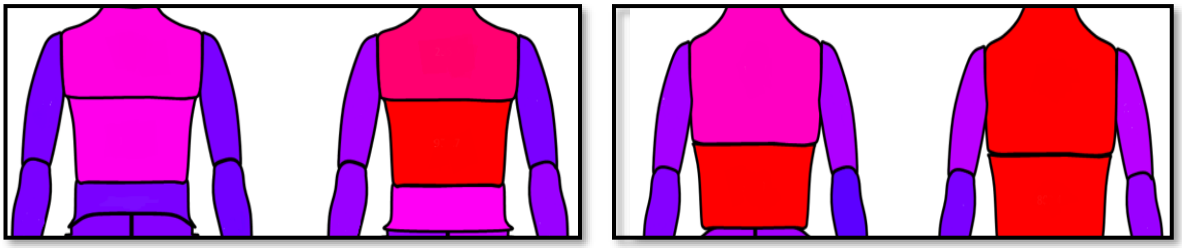


Figure 41.Evaporative resistance of Covert on male front/back (left) and female front/back (right)

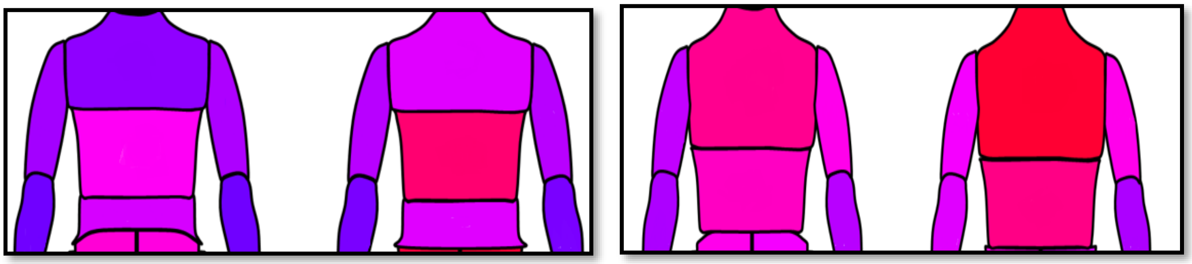


Figure 42. Thermal insulation of Overt on male front/back (left) and female front/back (right)

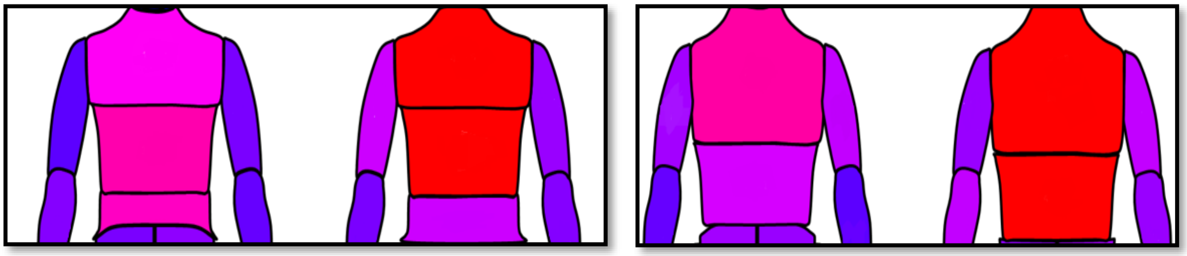


Figure 43. Evaporative resistance of Overt on male front/back (left) and female front/back (right)

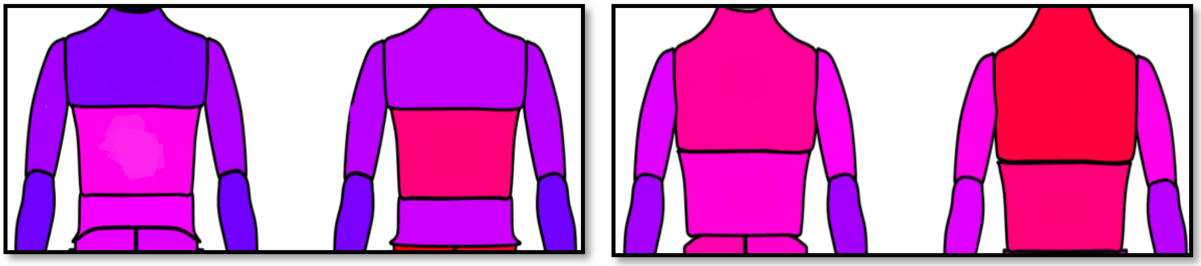


Figure 44. Thermal insulation of ballistic vest with hard plates (HP) on male front/back (left) and female front/back (right)

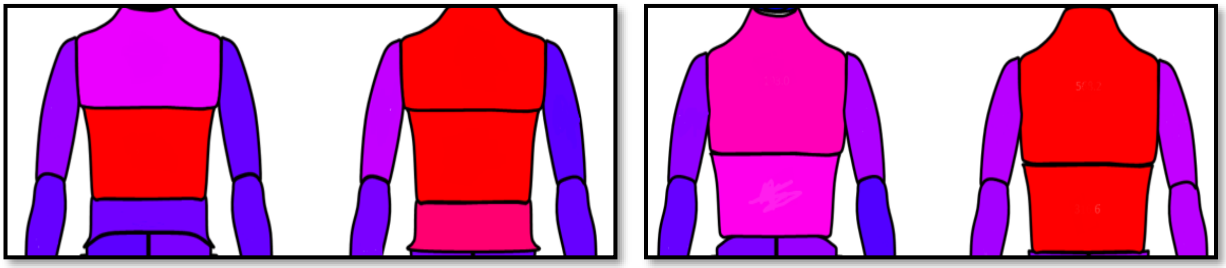


Figure 45. Evaporative resistance of HP on male front/back (left) and female front/back (right)

In the turnout suit, R_t & R_{et} were higher in the female torso area in all zones (Figures 38 & 39) both in front and back due to the curvature and air gaps created by it. In covert, R_t is higher in the female chest area and shoulders compared to male manikin R_{et} is higher in the female stomach, shoulder and back areas whereas male manikin had higher in the midback area R_{et} (Figure 40 & 41). Overt female torso had higher R_t in all zones compared to male torso (Figure 42) and male torso had consistent higher R_{et} in the whole torso area whereas female had higher R_{et} in the shoulder and back area (Figure 43). Ballistic vest with hard plates had higher R_t and R_{et} in the whole female torso area (Figures 44 & 45). However, male torso had higher R_{et} in the shoulder, midback and lower back area due to the flat surface, thereby, the snug fit of the ballistic vest and hard plates. The front torso of the female manikin in HP showed that there was some kind of evaporative heat loss in the stomach area due to the curvature of the female anatomy and air gaps due to the fit of the vest with hard plates

5.2 Thermal modelling (Task 3 & 4 results)

The intrinsic thermal and evaporative resistance values for station uniform (SU) and station uniform with ballistic vest (SUV) ensembles acquired from lab test data from both male and female manikins were used for thermal modeling. TAITherm^{TM} (version 2024.1.2) 3D thermal human comfort simulation software was utilized that predicts temperatures using transient or steady-state analysis. It uses clothing data, environmental conditions, and a work protocol input from the user to solve the complex heat and moisture transfer mechanism and estimate the body's physiological responses[182]

The simulations were conducted under a controlled ambient environment of 30 °C air temperature and 50 % relative humidity, representing a warm-humid but sub-extreme condition that is commonly encountered during fireground operations, training activities, and emergency medical responses when firefighters may be required to wear turnout gear and ballistic vests simultaneously. These environmental conditions were intentionally selected to impose a moderate yet physiologically meaningful thermal load that is sufficient to challenge thermoregulatory capacity without immediately driving the model to uncompensable heat strain. This approach allows for clearer discrimination of incremental differences in heat strain attributable to ensemble configuration, rather than overwhelming the system with extreme environmental stress that could mask clothing-related effects. The choice of 30 °C and 50 % RH is particularly relevant for evaluating the interaction between ballistic body armor and firefighter protective ensembles, as these conditions place substantial emphasis on evaporative heat loss, the primary avenue for thermal regulation at elevated metabolic rates. At 50 % relative humidity, sweat evaporation is partially constrained but not fully suppressed, allowing differences in ventilation, moisture permeability, and garment layering to emerge in the predicted responses. Consequently, these conditions are well-suited for identifying ensemble-driven variations in core temperature rise, mean skin temperature, sweating response, and cardiovascular strain, while maintaining ecological validity for real-world firefighter deployment scenarios.

Physiological responses were simulated using TAITherm, a multi-node thermophysiological model that resolves the human body into anatomically distinct segments and tissue layers, including core, muscle, fat, and skin compartments. The model dynamically solves heat-balance equations for each node, accounting for metabolic heat production, blood perfusion, conductive and convective heat transfer, radiative exchange, evaporative heat loss, and respiratory heat exchange. Thermoregulatory control mechanisms such as vasodilation, vasoconstriction, sweating, and shivering thresholds are governed by deviations of core and mean skin temperatures from set-point values. Clothing effects are incorporated through experimentally measured thermal insulation (R_t) and evaporative resistance (R_{et}) values, enabling the model to directly couple garment properties with physiological heat storage and dissipation.

A fundamental heat-balance perspective indicates R_t governs dry heat loss, R_{et} regulates evaporative heat loss, and core/skin temperature (together with cardiac output) increases when the necessary heat loss surpasses the dissipative capacity of clothes and the environment.

$R_t + R_{et}$, along with a basic heat balance can predict using a standard steady-state heat balance:

$$S = (M - W) - (C + R) - E$$

where, S= heat storage; M= metabolic heat production; W= external work; C= convective heat loss; R= radiative heat loss; E= evaporative heat loss

Clothing “resistances” approximation of Dry heat loss capacity (C+R) and Evaporative heat loss capacity (E) are the following:

$$(C + R) \approx \frac{T_{sk} - T_a}{R_t}$$

$$E \approx \frac{P_{sk} - P_a}{R_{et}}$$

From the heat-balance perspective, the direction of thermophysiological responses can generally be anticipated from ensemble thermal resistance (R_t) and evaporative resistance (R_{et}). An increase in R_t reduces dry heat transfer by convection and radiation (C + R), thereby elevating mean skin temperature and, over time, core temperature, particularly when ambient temperature is lower than skin temperature and dry heat loss remains a viable cooling pathway. Similarly, an increase in R_{et} limits evaporative heat loss (E), accelerating body heat storage (S) and leading to a rise in core temperature, with this effect becoming dominant under warm or humid environmental conditions and at moderate to high metabolic rates where evaporation represents the primary way of heat dissipation. When ensembles substantially increase R_{et} such as through the inclusion of moisture barriers or additional ballistic layers, core temperature is therefore expected to track changes in R_{et} more closely than changes in R_t under warm conditions. Cardiovascular responses are typically aligned with this thermal strain, as elevations in skin and core temperatures stimulate vasodilation and increased skin blood flow, resulting in higher cardiac output to support heat dissipation. Consequently, when ensembles are ranked according to overall heat-loss limitation, characterized by combined increases in R_t and R_{et}, a simplified heat-balance framework is generally sufficient to predict which configurations will impose greater thermal burden and which will remain comparatively cooler under steady-state conditions. From the experimental results, we can see that E1-E2 have lower R_t and R_{et} compared to E3-E6.

5.2.1 Effect of gender

The simulation was conducted with the ambient temperature of 30°C and relative humidity of 50%. The activity level was 3MET with 20 minutes rest and 20 minutes walking cycle where total activity time was 120 minutes for the 50th percentile male and female

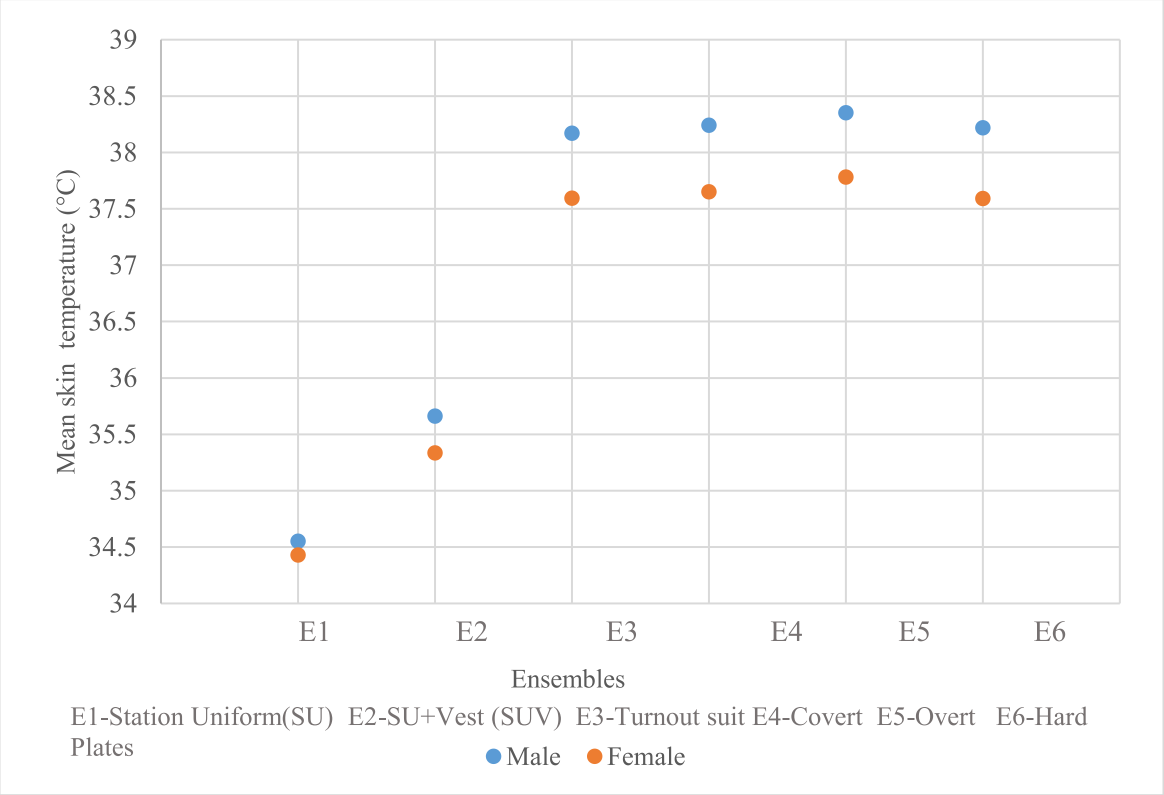


Figure 46. Effect of gender on mean skin temperature

The results showed that mean skin temperature was always higher for male and lower for female. The highest mean skin temperature was for male in overt, covert and hard plates (38.35°C) ensembles. The lowest skin temperature was for female in station uniform (34.42°C).

The results indicate a gender-based difference in the thermoregulatory responses. Males wearing overt, covert, and hard plate ensembles had the highest measured skin temperature (38.35°C), which indicates greater heat retention. This is likely caused by the reduction of evaporative cooling efficiency and increase in metabolic heat production while wearing heavy gear. On the other hand, station uniforms for female had the lowest skin temperature (34.42°C), which shows that lighter clothing dissipates heat more effectively. These results demonstrate how clothing insulation and physiological variations affect thermal balance.

Additionally, on average, the simulation model predicted that female responses tended to have lower mean skin temperatures than male responses in the same environmental condition primarily because women typically had less muscle mass than men, which generated less heat through metabolic activity, contributing to lower skin temperature than men [183]. Another possible explanation could be the higher body fat percentage in women as classified by ACSM (2014). Because of this relationship, the increased body fat has been associated with reduced T_{sk} [184]. Estrogen hormone in women increases peripheral vasoconstriction, which reduces blood flow to the skin. Reduced skin perfusion limits the heat exchange between the skin and the environment, leading to a lower skin temperature [185]

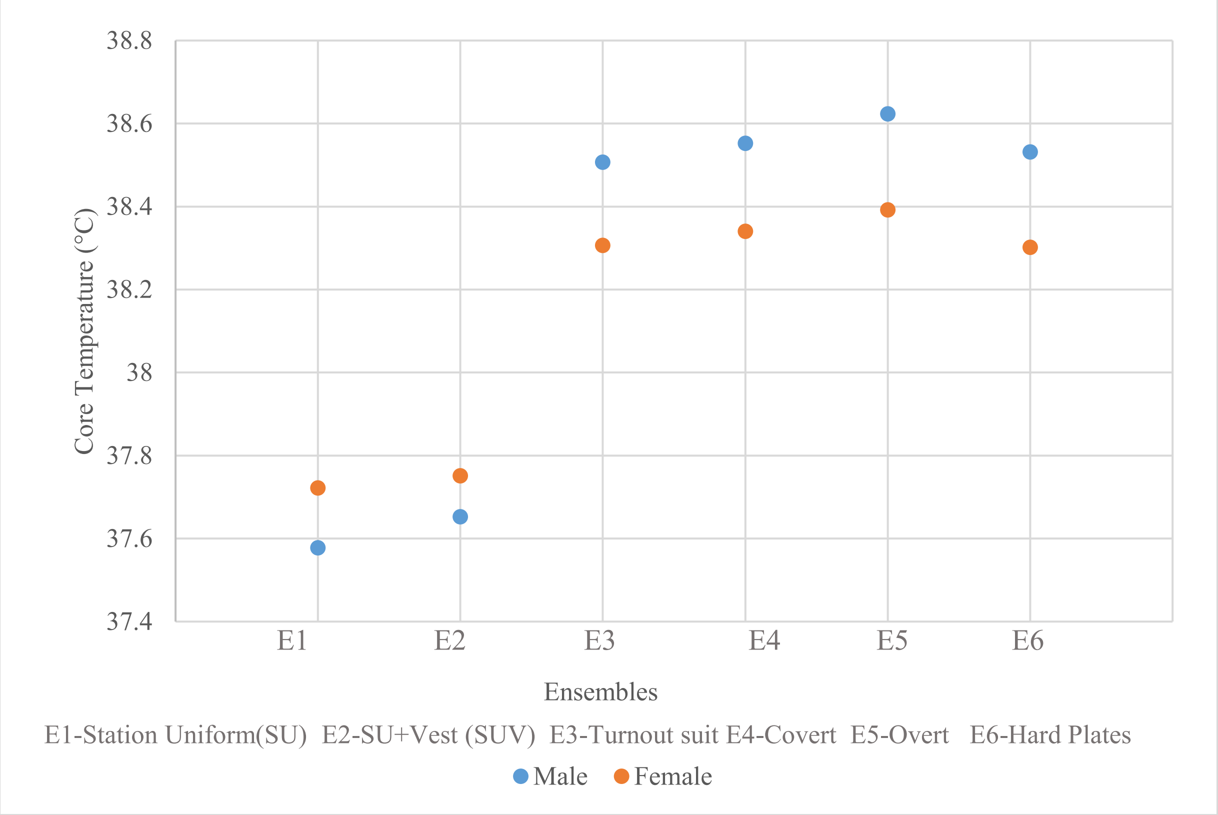


Figure 47. Effect of gender on core temperature

The results showed (Fig. 47) that core temperature started at a higher temperature point for male than female. Additionally, core temperature was higher for male than female in overt, covert and hard plates (38.62°C) ensembles. However, male core temperature was lower in station uniform and station uniform with ballistic vest ensembles than female. The lowest skin temperature was for male in station uniform (37.62°C). The reversal of the pattern in station uniform and station uniform with ballistic vests suggested that females are more efficient in heat dissipation in lighter ensembles than heavier clothing due to the physiological difference.

Usually, males tend to have a slightly higher core temperature than females because males typically have a higher basal metabolic rate due to greater lean body mass (muscle tissue), which is metabolically active and generates more heat. This increased heat production raises core body temperature. [186]. Also, males have a lower body surface area to mass ratio than females. It would provide a low heat loss surface area relative to the heat production volume.[183]. Additionally, males tend to have a slightly higher thermoregulatory set point in the hypothalamus (the brain region responsible for temperature control). This set point aligns with their higher metabolic heat production. [187]

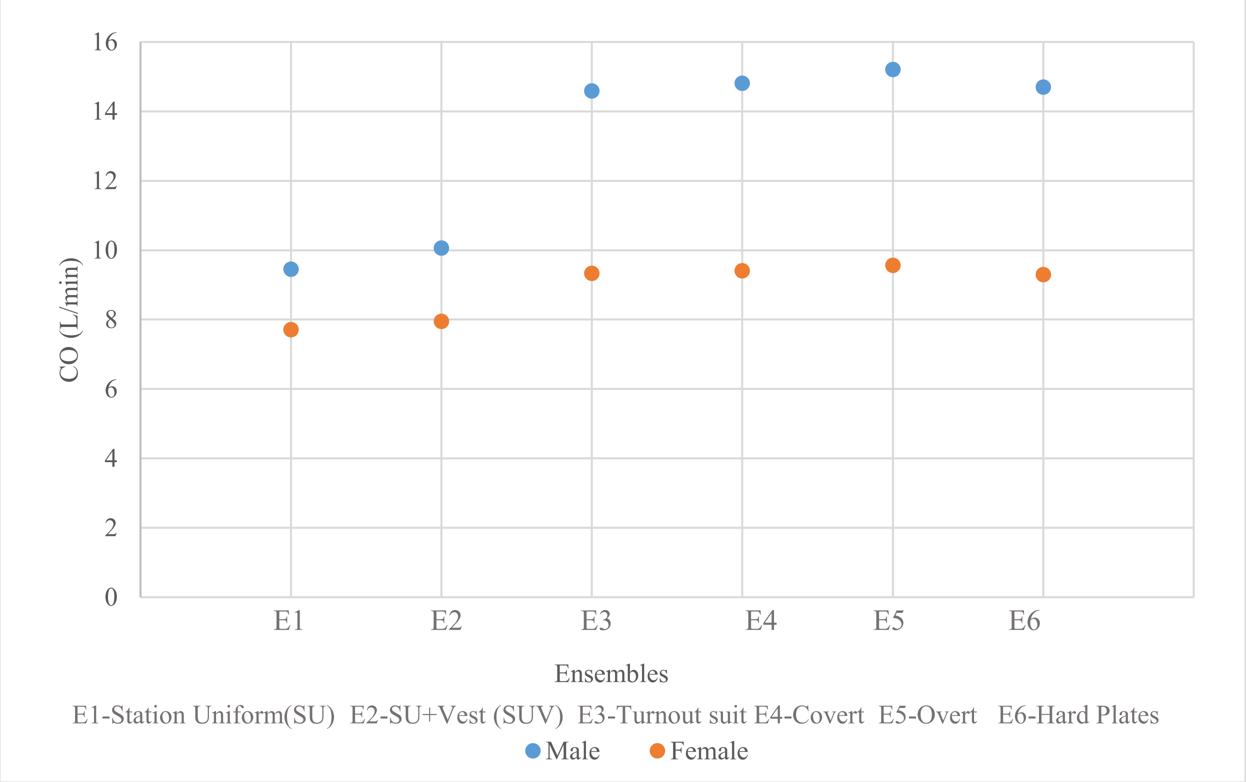


Figure 48. Effect of gender on cardiac output

The results showed (Fig 48) that cardiac output was always higher for male than female in all ensembles. The highest cardiac output was for male in overt, covert and hard plates (15.5 L/min) ensembles. The lowest cardiac output was for female in station uniform (7.94 L/min). The higher cardiac output of male than female aligns with the previous findings in physiological differences between males and females where male heart size is bigger than female, resulting in a higher stroke volume and higher cardiac output. Independent from the body size, women showed to have smaller ventricular chambers and smaller arterial diameter, and length compared to men of the same age and race which may limit blood flow capacity. Therefore, the stroke volume is also smaller in women, being approximately 22.9% less than that in men [188]. Also, cardiac output is proportional to metabolic demand. Females typically have a lower resting metabolic rate than males due to differences in body composition (e.g., less lean mass). As a result, females have lower baseline oxygen demands, requiring less cardiac output to supply tissues with oxygen [189].

5.2.2 Effect of rest time

Simulation was conducted with with the ambient temperature of 30°C and relative humidity of 50%. The activity level was walking at 3MET with 20 minutes, 10 minutes and no rest time where total activity time was 120 minutes.

5.2.2.1 Mean skin temperature

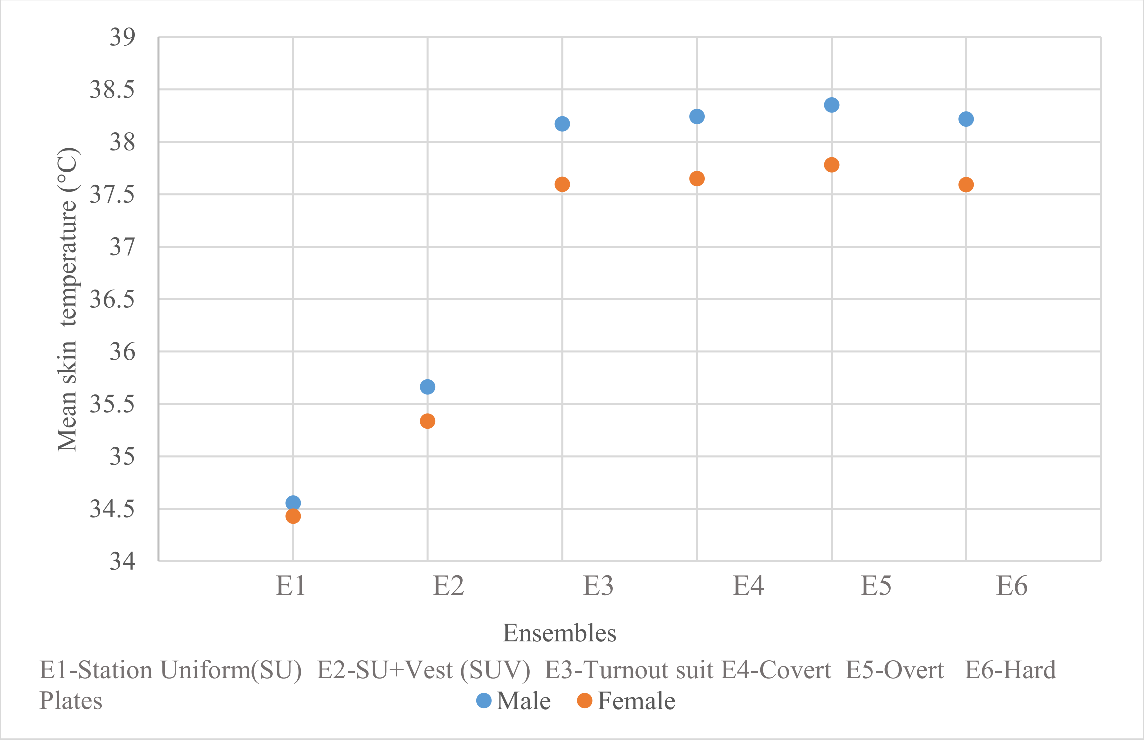


Figure 49. Mean skin temperature with 20 minutes rest cycle

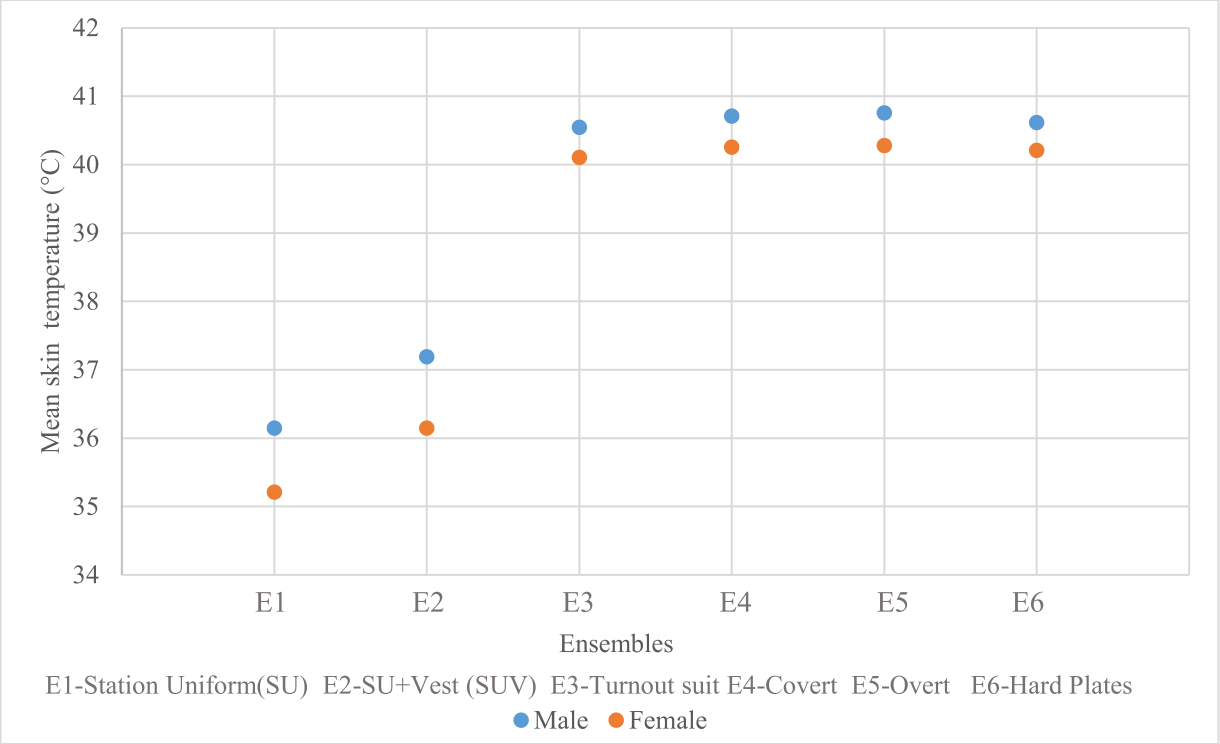


Figure 50. Mean skin temperature with 10 minutes rest cycle

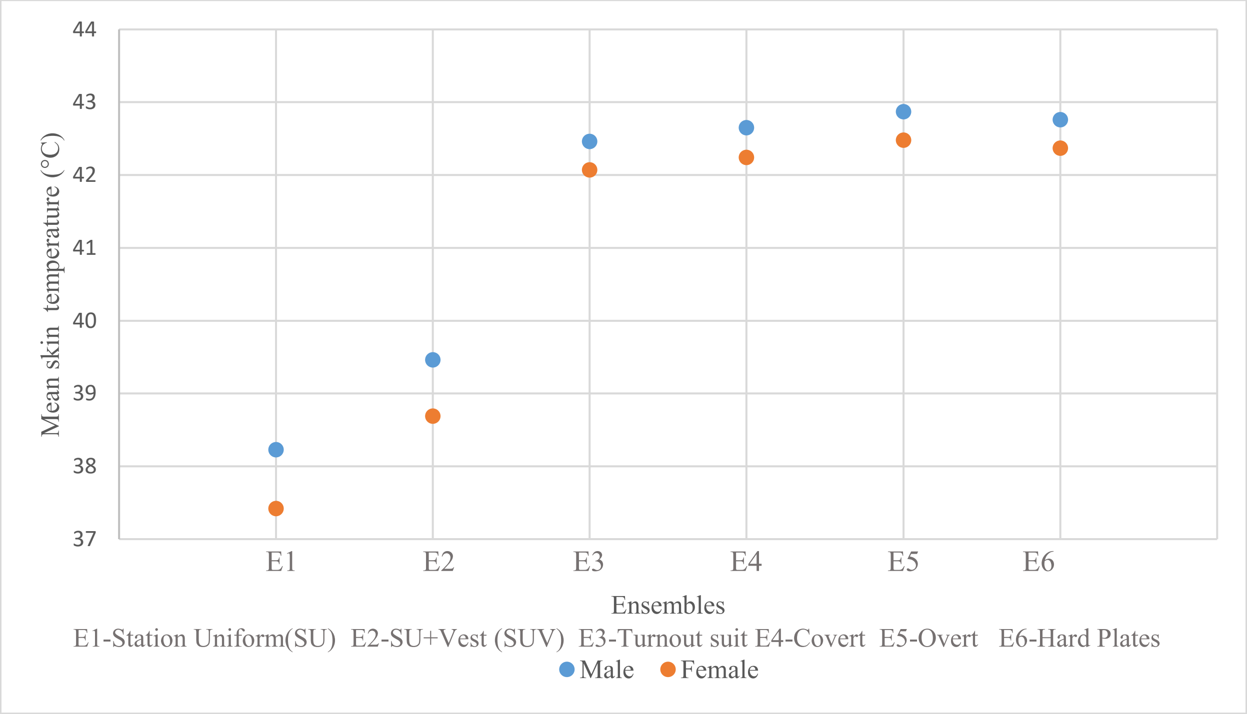


Figure 51. Mean skin temperature with no rest time

The results showed that across all the ensembles, E5 showed the highest temperatures in all scenarios. With 20 minutes of rest time, the highest mean skin temperature was 38.35°C. However, at 20 the highest mean skin temperature was 39.08°C. With no rest cycle, the highest temperature was 42.87°C. The progressive elevation of mean skin temperature with reduced rest time indicated that the cumulative effect of thermal strain when less or no resting time was provided. The trend indicated that inadequate rest periods cycle more metabolic heat production and hinders heat dissipation leading to excessive heat retention and a higher risk of heat strain and possibly hyperthermia.

5.2.2.2 Core temperature

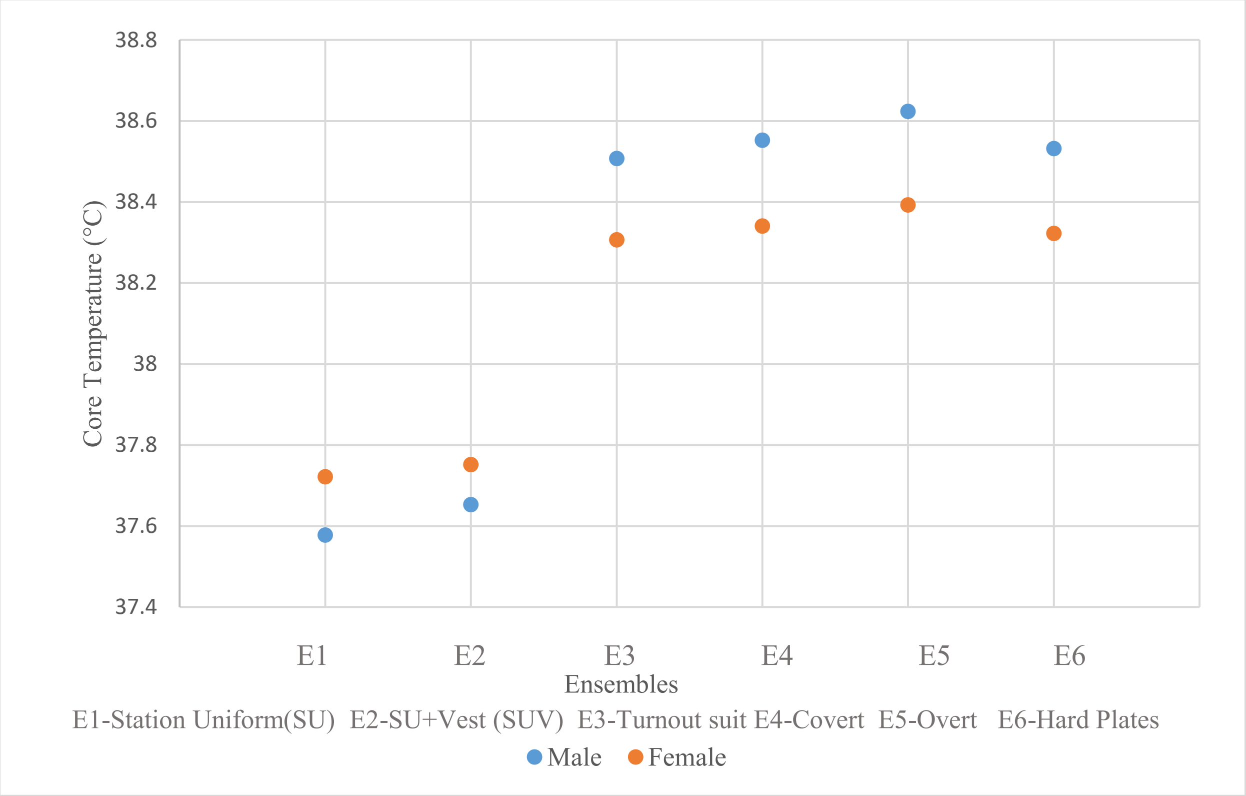


Figure 52. Core temperature with 20 minutes rest cycle

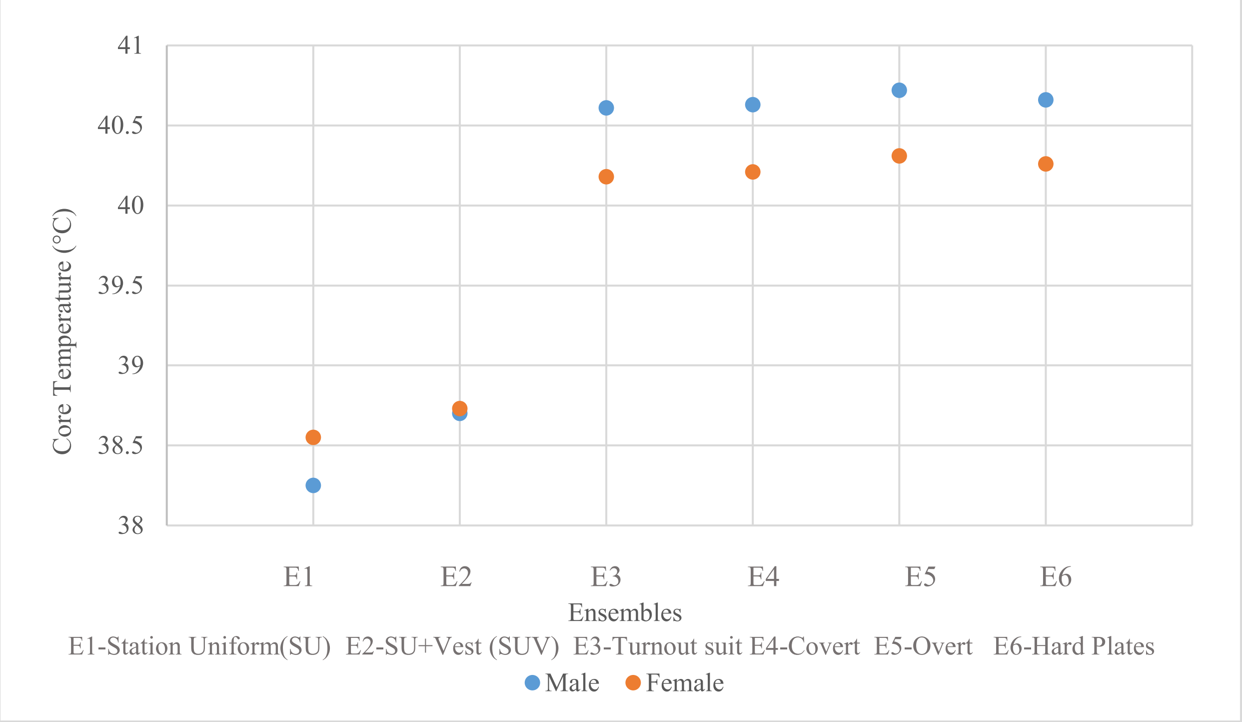


Figure 53. Core temperature with 10 minutes rest cycle

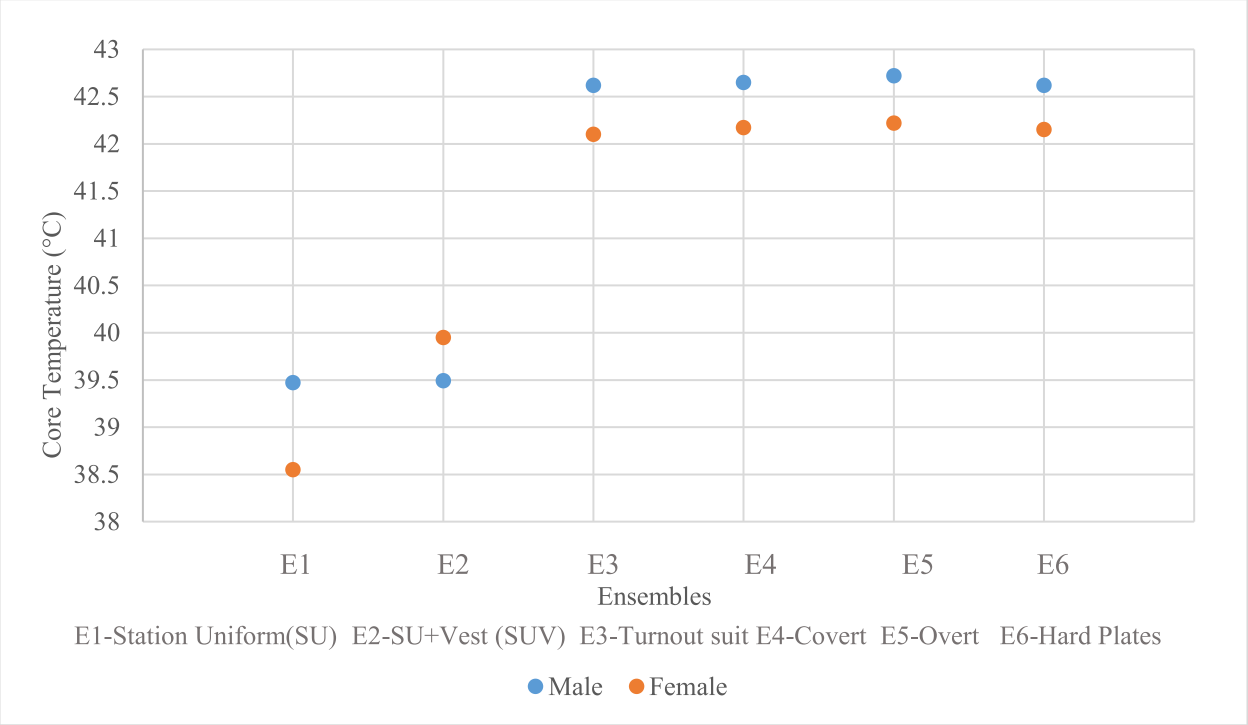


Figure 54. Core temperature with no rest time

The results showed that with 20 minutes (Fig 52) and 10 minutes (Fig 53) rest time, core temperature was higher for male than female in overt, covert and hard plates (38.62°C) ensembles. However, with no rest time (Fig 54), female core temperatures were always lower than male. Additionally, it took 120 minutes to reach the core temperature to 38.62°C in 20 minutes rest cycle for overt, covert and hard plates ensemble in male. On the other hand, it took 64 minutes to reach that core temperature in 10 minutes rest cycle. With no rest cycle, it took 50 minutes. The results suggested that there was a faster increase in core temperature with reduced or no rest period. It can be inferred from the results that more frequent or prolonged intervals between work rest time might delay the accumulation of heat inside the body and ensembles, however, it would not entirely prevent the rise in core temperature. The results emphasized the need to optimize rest period to reduce heat strain in occupational settings where wearing firefighter suit with ballistic gear is required for a prolonged time.

5.2.2.3 Cardiac output

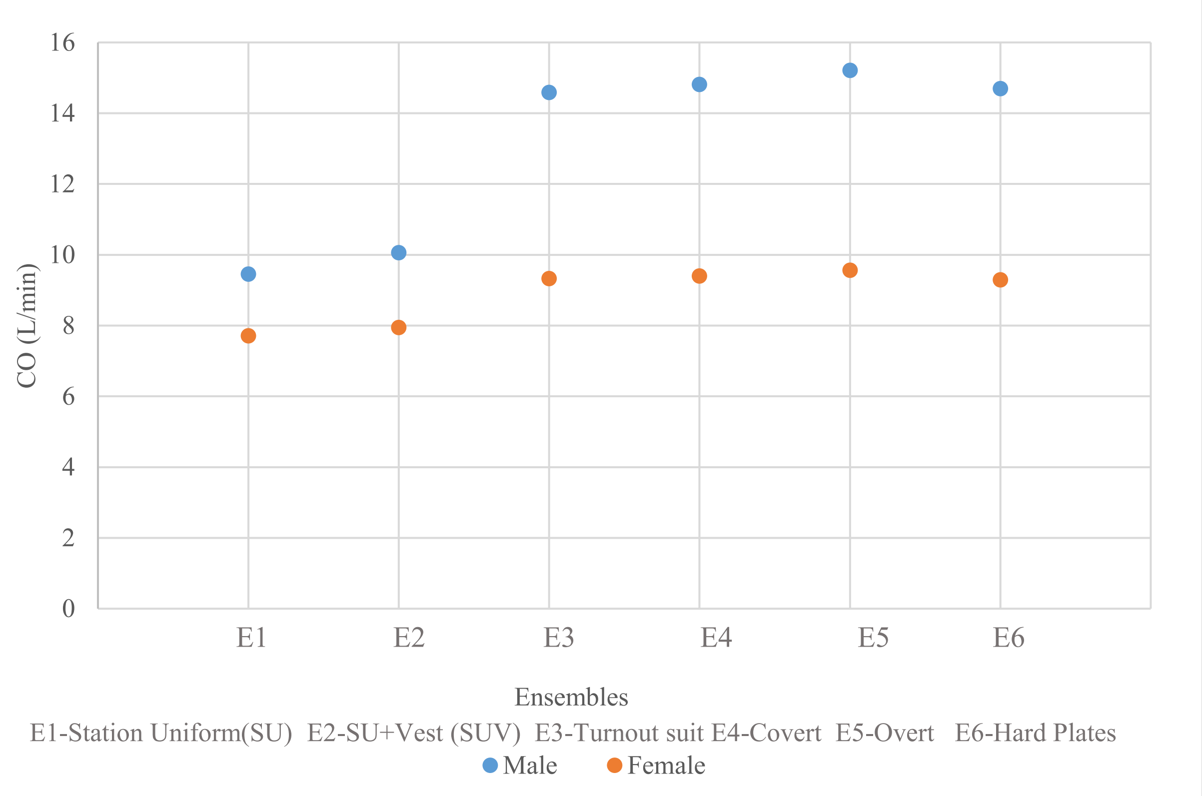


Figure 55. Cardiac output with 20 minutes rest cycle

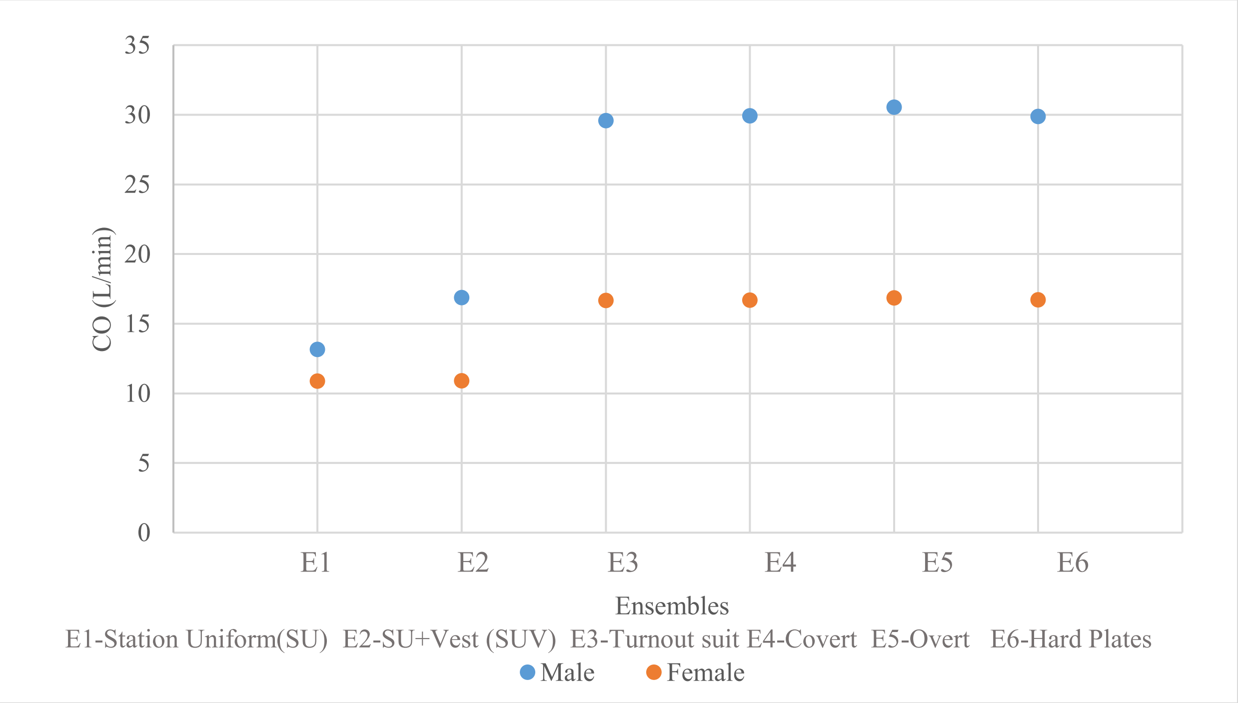


Figure 56. Cardiac output with 10 minutes rest cycle

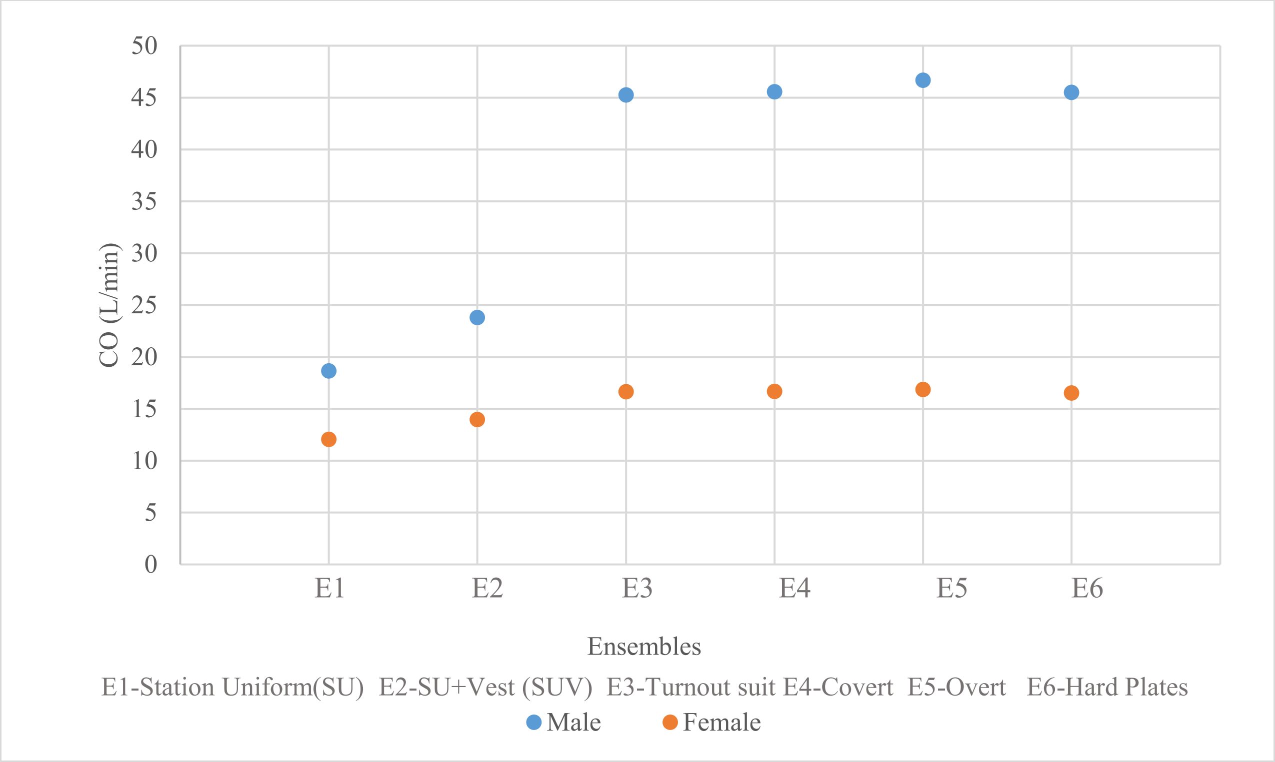


Figure 57. Cardiac output with no rest time

The results showed that at 20 minutes rest cycle (Fig 55), highest cardiac output was 15 L/min (for male overt, covert, hard plates and turnout suit ensembles). In the 10 minutes rest cycle (Fig 56), there was a 100% increase in the highest cardiac output for the same ensembles (31 L/min). With no rest time (Fig 57), there was an increase of 300% in the cardiac output (46 L/min). The findings demonstrate the significant cardiovascular strain caused by shorter rest periods during physical activity while wearing protective gear. The increasing cardiovascular strain as rest intervals are reduced was observed by the progressive increase in cardiac output from 15 L/min in the 20-minute rest cycle to 31 L/min (100% increase) in the 10-minute rest cycle and 46 L/min (300% increase) with no rest. This implies that insufficient recovery time makes the heart work harder to maintain oxygen delivery and thermoregulation, which may cause cardiovascular fatigue or heat strain to develop early. The significance of scheduled rest time in reducing physiological stress was demonstrated in the simulation by the exponential increase in cardiac output with decreasing rest, especially in high-risk occupational situations in firefighting or military operations where heavy gear is often used.

5.2.3 Data validation for female manikin

5.2.3.1 Internal validation

The internal validation was performed by simulating female physiological responses in TAITherm using two different input parameter sets: one derived from male physiological data and one derived from female-specific data to evaluate the internal consistency, and scaling behavior of the TAITherm thermophysiological model. This approach was not intended to compare male and female heat strain directly, but rather to test whether TAITherm produces stable and physically consistent female response predictions when driven by alternative, yet physiologically reasonable datasets under identical environmental, metabolic, and clothing boundary conditions. The protocol for this analysis was 30°C temperature, 50% relative humidity, walking at 5MET and resting at 1.1 MET. The total time was 120 minutes.

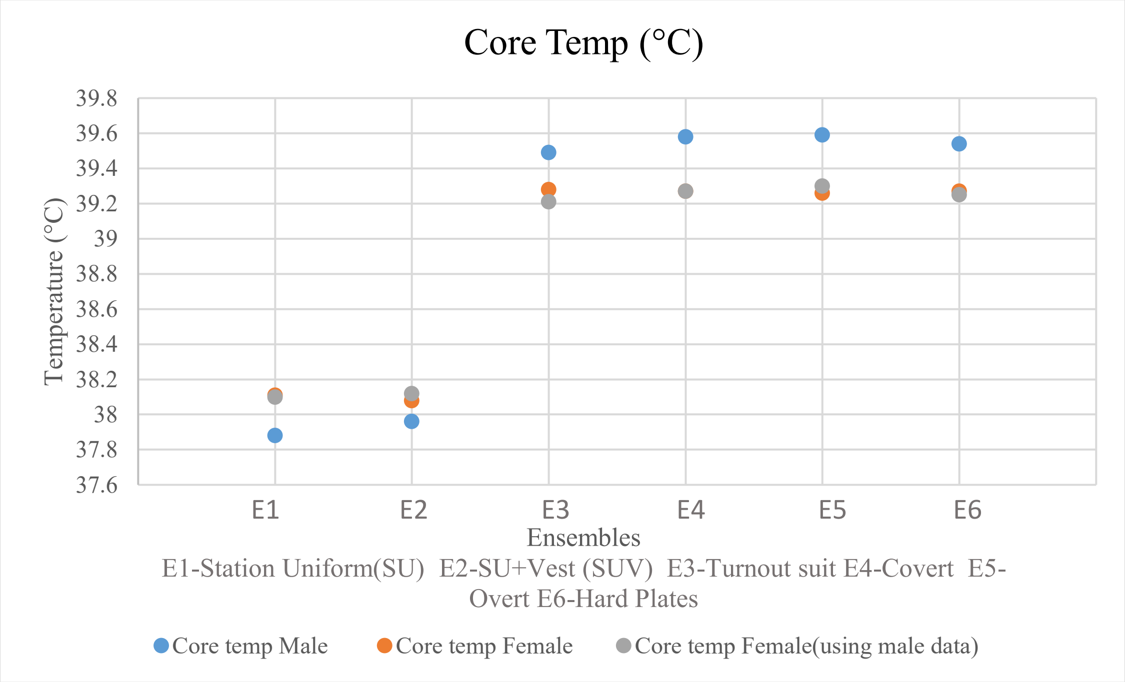


Figure 58. Core temperature for internal validation

Core temperatures across E1 to E6 ensembles were from about 37.8°C to 39.6°C, covering both normal resting values while wearing station uniform (SU) and SU with ballistic vests (~37.5-38°C) and elevated heat strain responses (>39°C) while wearing turnout suit (TS) with and without ballistic vests. This range indicated exposure to heat or physical exertion sufficient to drive core body temperatures into a physiologically stressed state. The SU→SUV change is trivial; the big jump is at TS. After that, vest position (covert/overt/HP) did not meaningfully shift core temperature. Male data (blue) showed a sharp rise from ~37.8°C (E1-E2) to ~39.6°C (E3-E6), indicating sustained heat strain. Female data (orange) followed a similar upward trajectory but consistently remains ~0.2-0.3°C lower than male values with added layers of turnout suit and ballistic vests (E3-E6). Female core temperature modeled with male data (gray) tended to align closely with the actual female response but slightly overestimated values at early timepoints and converges around the later ones. The female core temperature '(using male data)" values showed relatively good alignment with actual female data. This indicated that male-derived predictive models may approximate female responses under heat stress, but the early-time differences highlight potential gender-specific dynamics in heat storage or distribution.

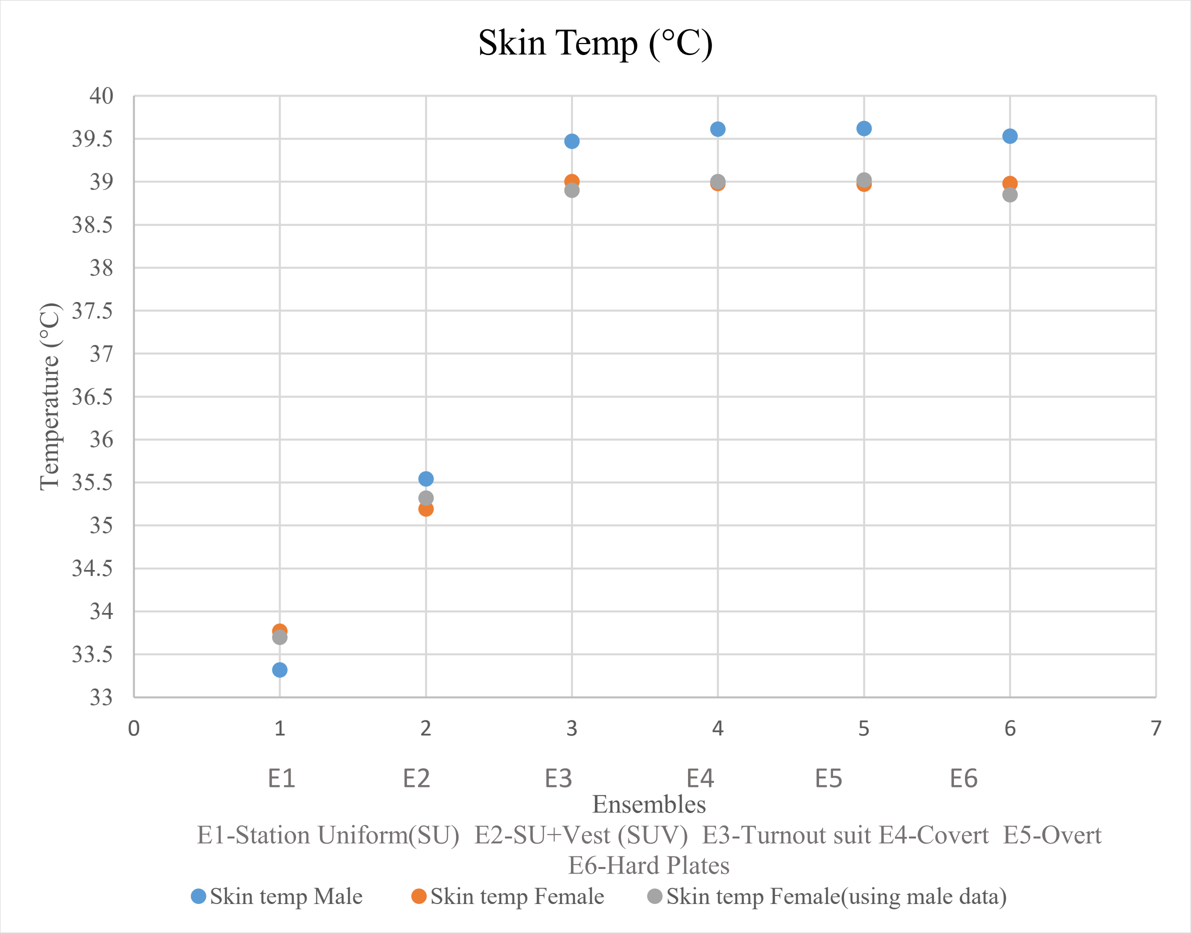


Figure 59. Mean skin temperature for internal validation

Mean skin temperature for male ~33.3 °C (SU) → ~35.6 °C (SUV); female ~33.7 °C (SU) → ~35.2 °C (SUV) and female using male data: ~33.6 °C (SU) → ~35.3 °C (SUV). Adding the ballistic vest (SUV) elevated skin temperature by ~2 °C in both genders, indicating that vest increased thermal & evaporative resistance and reduced heat dissipation at the skin surface. There was a significant jump from ~35 °C → ~39 °C when turnout suit (E3) was employed. Males had ~0.5 °C higher skin temps than females, consistent with higher metabolic heat generation. Female (using male data) slightly underestimated actual female skin temperatures for turnout suit. Once turnout suit was employed, the combination of vest for covert (E4), overt (E5), and hard plate (E6) did not meaningfully alter skin temperature and the variations was ≤0.1 °C between actual female T_{sk} and female T_{sk} “using male data”. Therefore, actual female mean skin temperature (orange) results showed good alignment with the female mean skin temperature “using male data” (gray).

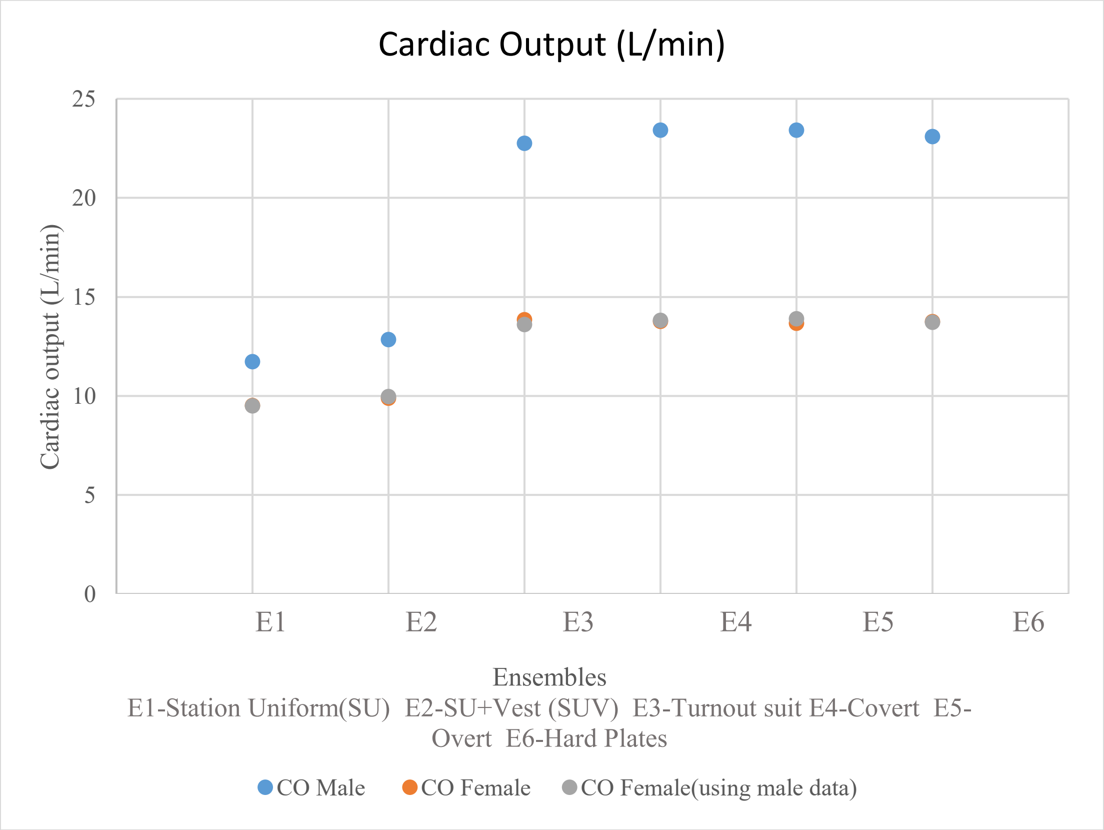


Figure 60. Cardiac output for internal validation

Male cardiac output elevated from 12 to ~13L/min (SU→SUV), then a step to ~23–23.5 L/min for turnout suit (TS) and TS with covert, overt, and hard plates combination with a flat plateau (≤0.7 L/min variation). Therefore, actual female mean skin temperature (orange) results showed good alignment with the female mean skin temperature "using male data" (gray).

Female (male-data model) followed the actual female values closely across all ensembles. Under TS and all vest types, males sustained ~9-10 L/min higher CO than females. This finding indicated a higher absolute metabolic rate and larger stroke volume with larger body size. Despite higher male CO, males also show higher core and skin temperatures when wearing turnout suit (TS) ensembles. This is consistent with greater heat production and a stronger need for skin blood flow that the clothing system cannot fully meet.

By applying male-derived inputs to a female anthropometric model and comparing the resulting outputs with those generated using female-derived inputs, the analysis assessed whether predicted female core temperature, mean skin temperature, and cardiac output were susceptible to the origin of physiological input data, or whether ensemble-level heat-transfer constraints dominated the response. The close agreement between the two simulations indicated that, under the conditions examined, TAITherm appropriately scaled physiological responses based on gender-specific physiology and imposed boundary conditions, rather than being overly dependent on empirical inputs. This finding demonstrated that the model's governing heat-transfer and thermoregulatory equations are internally coherent.

5.2.3.2 External validation (JOS-3 vs TAITherm)

External validation was conducted by comparing physiological predictions generated by TAITherm with those obtained from the JOS-3 thermophysiological model to assess the credibility, and physical grounding of the simulation results. To justify the choice of JOS-3 for external validation, it is important to contrast it with other commonly used heat strain models, including USARIEM heat strain models and FAME, and to examine why those frameworks are less appropriate for validating clothing-specific thermophysiological mechanisms.

USARIEM models are designed primarily to predict operational heat strain in military contexts, emphasizing endurance limits, hydration status, work–rest cycles, and environmental exposure. While highly effective for field decision support, these models typically employ simplified clothing representations and are not designed to select gender or to differentiate or predict male vs female physiological responses under heat strain. In the FAME model, clothing is typically represented using predefined garment categories or default ensembles, rather than user-specified thermal and evaporative resistance inputs. As a result, investigators are limited to selecting from a fixed set of clothing options, with no capability to independently prescribe measured R_t and R_{et} values or to construct layered clothing systems. Consequently, complex ensemble configurations such as combinations of station uniforms, turnout gear, and ballistic vests cannot be explicitly modeled.

While TAITherm provides a high-resolution, three-dimensional representation of human-clothing-environment heat transfer, its complexity and proprietary structure necessitate validation against an independent, openly documented model based on first-principles heat balance. JOS-3 was selected for this purpose because it is a well-established, multi-node human thermoregulation model implemented in Python, with transparent governing equations describing metabolic heat production, dry and evaporative heat exchange, and active thermoregulatory control [190]. The objective of this external validation was to evaluate the credibility and physiological consistency of the female thermophysiological predictions generated in TAITherm by comparing them against outputs from the independently developed JOS-3 model.

To achieve this, identical environmental conditions, metabolic rates, (30°C temperature 50% relative humidity, walking at 5 MET and resting at 1.1 MET. The total time was 120 minutes), and ensemble-level thermal and evaporative resistance inputs were applied in both modeling frameworks. Female physiological outputs generated using JOS-3 were then directly compared with corresponding female predictions from TAITherm to evaluate agreement in the magnitude, and prediction of core temperature.

Table 8. Male core temperatures in JOS-3 and TAITherm

Ensemble (Male)	**JOS-3 (°C)**	**TAITherm (°C)**	**Δ (TAI − JOS)**
SU	37.06	37.6	0.54
SUV	37.07	37.71	0.64
TS	37.29	38.54	1.25
Covert	37.38	38.66	1.28
Overt	37.39	38.69	1.30
Hard Plates	37.52	38.79	1.27

Table 9. Female core temperatures in JOS-3 and TAITherm

Ensemble (Female)	**JOS-3 (°C)**	**TAITherm (°C)**	**Δ (TAI − JOS)**
SU	37.13	37.75	0.62
SUV	37.19	37.80	0.61
TS	37.40	38.36	0.96
Covert	37.42	38.46	1.04
Overt	37.43	38.42	0.99
Hard Plates	37.58	38.56	0.98

To assess the reliability of the TAITherm thermophysiological model for predicting firefighter core temperature under varying clothing systems, its outputs were systematically compared with those generated by JOS-3. The JOS-3 model is a widely applied multi-node human thermoregulation framework that characterizes the body’s thermal behavior by partitioning it into numerous anatomical segments and tissue layers. Each node corresponds to a defined body region, with heat-transfer relationships describing energy exchange among adjacent nodes [191]. This modeling approach has proven valuable for investigating thermal comfort and physiological heat-strain responses across diverse environmental conditions and activity intensities. TAITherm integrates both thermal resistance (R_t) and evaporative resistance (R_{et}) into a full human heat-balance framework, whereas JOS-3 (Python) integrates thermal resistance (R_t) but includes evaporative resistance (R_{et}) in predicting core temperature indirectly through the evaporative heat-loss pathway, not as a standalone variable. Given this fundamental difference in physical formulation, absolute numerical agreement was not expected. Instead, the objective of this comparison was to determine whether JOS-3 reproduced the same directional trends, ensemble ranking, and gender-specific response patterns observed in TAITherm. Such an agreement would indicate that TAITherm is valid for relative and comparative heat-strain assessment, even if conservative bias exists in absolute temperature prediction.

Separate analyses were conducted for female and male simulations across six ensemble configurations: station uniform (SU), station uniform with vest (SUV), station uniform with turnout suit (TS), covert vest, overt vest, and hard plate armor.

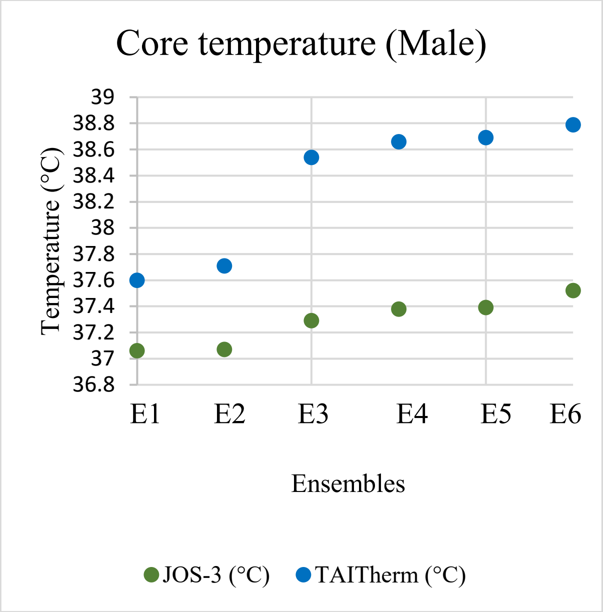


Figure 61. TAITherm vs JOS-3 T_{re} in males

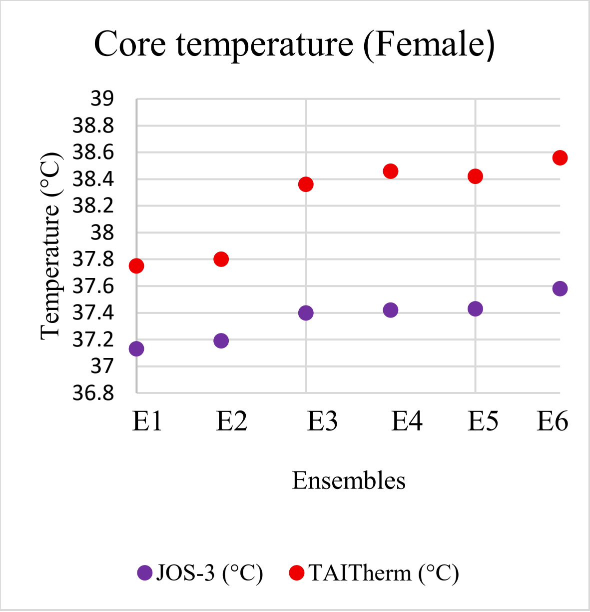


Figure 62. TAITherm vs JOS-3 T_{re} in females

Both TAITherm and JOS-3 independently reproduced the same gender-based physiological hierarchy across all ensembles in Figs 61 and 62. Across all clothing conditions, JOS-3 and TAITherm showed similar pattern both for male and female. This consistent gender-dependent response across two independent modeling frameworks strengthens confidence in the physiological validity of both simulation approaches. The comparative evaluation of TAITherm and JOS-3 core temperature predictions revealed a consistent and theoretically interpretable relationship between the two modeling frameworks. Because TAITherm incorporated both thermal resistance (R_t) and evaporative resistance (R_{et}) into the clothing-microenvironment heat balance, it provided a more comprehensive representation of the physiological constraints imposed by encapsulating and vapor-impermeable protective ensembles. In contrast, although JOS-3 explicitly modeled evaporative heat loss and sweating responses, the Python implementation did not permit user-defined evaporative resistance as an external clothing input. JOS-3 solved the human heat balance and explicitly computed evaporative heat loss (E) from the skin [190]. When R_{et} increases, E_{max} decreased and there is less sweat evaporation, therefore greater heat storage (S) and higher predicted core temperature. This effect is strongest in warm/humid conditions or at moderate-high metabolic rates, where evaporation is the dominant cooling mechanism. Because JOS-3 is a node-based model, R_{et} is applied at the segment or whole-body level rather than resolving local air gaps or fit effects. Thus, it captured first-order evaporative limitations, but not the spatial nuances that TAITherm can resolve.

So, in JOS-3, evaporative heat transfer was calculated internally based on environmental conditions, physiological control, and clothing insulation parameters [190]. Unlike TAITherm, which allowed independent specification of thermal insulation and evaporative resistance, JOS-3 incorporated evaporative heat transfer implicitly through its thermophysiological control algorithms and did not expose evaporative resistance as a user-settable parameter. JOS-3 incorporated evaporative resistance as a limiting factor on maximum evaporative heat loss and allowed relatively efficient sweat evaporation once sweating is initiated, with heat storage distributed across lumped body segments. This resulted in a more optimistic evaporative cooling response and smoother redistribution of heat, yielding lower predicted core temperatures. In contrast, TAITherm explicitly resolved regional clothing insulation, air-gap geometry, and microclimate constraints associated with layered turnout and ballistic systems, which may have imposed stronger evaporative bottlenecks and promoted localized heat trapping that propagated to the core. Thus, the lower core temperatures predicted by JOS-3 did not indicate omission of R_{et} or evaporative heat loss, but rather reflected a simplified, first-order representation of evaporation that captured global heat-balance behavior while underestimating the severity of clothing-induced evaporative restriction compared to TAITherm. This divergence reinforced the complementary roles of the two models: JOS-3 validates the fundamental heat-balance trends, while TAITherm revealed the higher, more conservative heat-strain outcomes arising from detailed clothing and fit effects. Despite these fundamental differences, the graphical comparison of model outputs for both male and female simulations (Figures 55 and 56) demonstrated excellent agreement in pattern, ensemble ranking, and gender-specific response, which is the central criterion for validating JOS-3 as a comparative modeling tool.

Based on graphical and numerical comparisons, TAITherm met the criteria for validation as a comparative, trend-based physiological model. Its predictions reproduced the same ensemble ranking, exhibit the same T_{re} male-female pattern, showed consistent directional sensitivity to added ballistic burden, and diverged from JOS-3 only in magnitude.

5.2.3.3 External validation with wear trial data

For external validation with wear trial, a study of Gagnon et al. (2009) [192] was selected. The wear trial protocol consisted of three intermittent bouts of semi-recumbent cycling, each lasting 30 min, separated by 15 min of inactive recovery, performed inside a whole-body direct air calorimeter maintained at 30 °C and 30% relative humidity. Six males and six females exercised at a constant metabolic heat production of approximately 500 W, verified by indirect calorimetry, ensuring equivalent internal heat loads between genders despite differences in relative exercise intensity. Participants wore standardized light clothing (~0.2-0.3 clo), and core temperature (rectal), metabolic heat production, and evaporative and dry heat loss were measured continuously, allowing minute-by-minute determination of dynamic heat balance and changes in body heat content across exercise and recovery phases

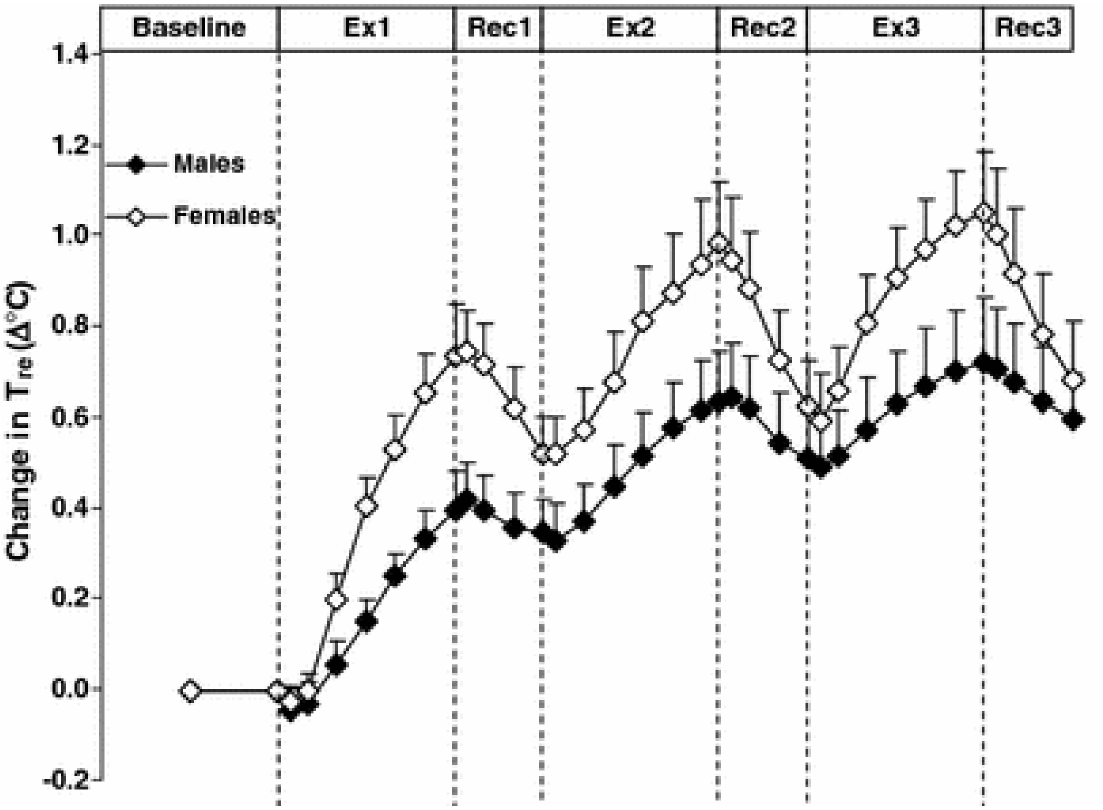


Figure 63. Core temperature differences between males and females in wear trial[192]

The experimental data (Fig 63) demonstrated a clear and reproducible pattern of progressive heat accumulation across repeated exercise-recovery cycles, characterized by stepwise increases in core temperature (ΔT_{re}) during exercise bouts and incomplete cooling during intervening recovery periods. Across all phases, females consistently exhibited greater increases in core temperature than males, with the magnitude of the gender difference increasing over successive bouts. Importantly, the experimental responses were nonlinear in both exercise and recovery, reflecting the dynamic balance between metabolic heat production, and physiological thermoregulatory constraints. These features provided a rigorous benchmark against which thermophysiological models must be evaluated.

Same protocol was conducted on JOS 3 and TAItherm and the results are following:

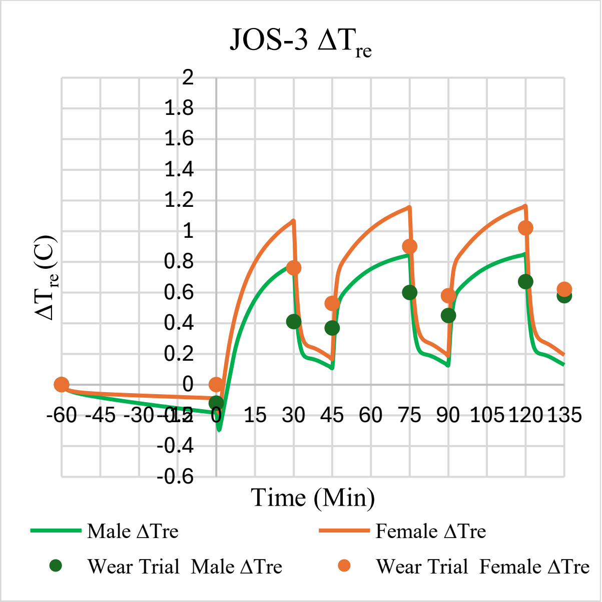


Figure 64. Core temperature differences between males and females in JOS-3

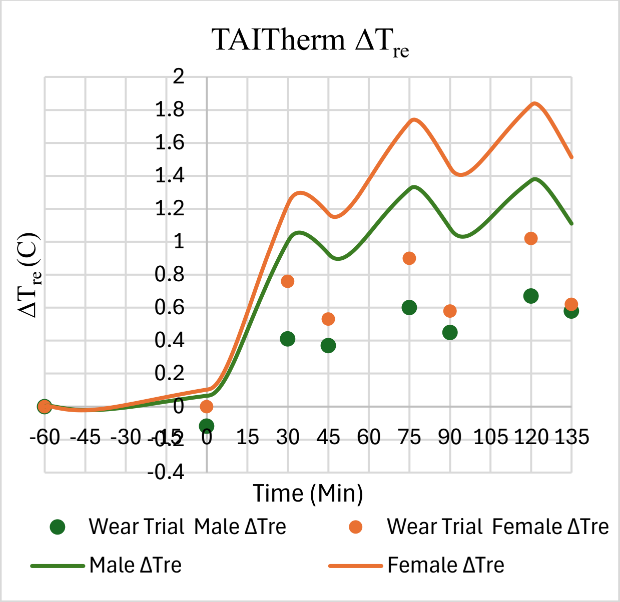


Figure 65. Core temperature differences between males and females in TAITherm

Compared with experimental data, the JOS-3 model successfully reproduced the overall temporal structure of the protocol (Figure 64), including discrete exercise recovery transitions and progressive increases in core temperature across bouts. The model also preserved the directionality of gender differences, with females showing higher elevations in core temperature than males throughout the protocol. However, despite these qualitative agreements, JOS-3 systematically underestimated cumulative heat storage. Recovery phases were characterized by overly rapid reductions in core temperature, resulting in lower end-recovery across successive exercise bouts. Additionally, JOS-3 predicted an exaggerated transient cooling response prior to exercise onset that was not observed experimentally, indicating excessive modeled heat loss under resting conditions.

In contrast, TAITherm demonstrated substantially closer agreement with the experimental data (Figure 65) across multiple dimensions of comparison dimensions in three specific ways. Firstly, TAITherm accurately reproduced the progressive increase in core temperature across repeated exercise bouts, closely matching the wear-trial pattern in which rectal temperature continued to rise from one bout to the next rather than fully recovering during rest. This cumulative heat storage was clearly visible in the experimental data and was preserved in the TAITherm predictions, whereas JOS-3 allowed core temperature to drop too much during recovery, reducing transfer to the following bouts. Secondly, TAITherm captured the magnitude of temperature change more realistically: while it slightly overestimated peak ΔT_{re} by approximately 0.2-0.4°C, the predicted values remained close to the experimental range, particularly for females during later bouts, whereas JOS-3 consistently underestimated peak and end-bout temperatures by ~0.3-0.6 °C. Thirdly, TAITherm reproduced the gender-specific divergence observed experimentally, with females showing greater cumulative heat strain than males, and the gap widening with continued exposure with an effect that closely mirrors the wear-trial results. Together, these agreements showed that TAITherm not only followed the same overall trend as the experimental data, but also captured the timing, accumulation, and relative magnitude of heat strain seen in human subjects. So TAITherm model reproduced the progressive accumulation of core temperature across repeated exercise bouts, the incomplete recovery between bouts, and the nonlinear rise and fall of ΔT_{re} observed experimentally. Gender differences were consistently maintained, with females exhibiting greater cumulative heat strain than males, and the divergence between gender increased with repeated exercise exposure, closely mirroring the empirical findings. Although TAITherm predicted slightly higher absolute elevations in core temperature than those reported experimentally, the relative magnitude, temporal evolution, and gender-specific trajectories aligned more closely with the observed physiological responses than those generated by JOS-3.

Overall, while both models reproduced the general structure and directional gender differences observed experimentally, TAITherm provided more physiological realism and closer agreement with the experimental data. TAITherm showed better-suited applications for more accurate prediction of cumulative heat strain and gender-specific thermoregulatory responses, whereas JOS-3 is more appropriately applied as a comparative or screening-level tool.

5.2.4 Effect of different RH%

The simulation protocol was designed to evaluate physiological responses under temperature of 32 °C, with relative humidity levels of 30% and 40% tested to capture the influence of moisture on heat exchange. The choice of 30% versus 40% relative humidity was intentional because this range represents a transitional zone rather than an extreme condition. As a result, differences in clothing evaporative resistance (R_{et}), layering, and fit were expected to emerge more clearly than they would at low humidity (where evaporation is highly efficient for all ensembles) or at comparatively high humidity (where evaporation is uniformly limited regardless of clothing design). Therefore, testing both humidity levels allowed assessment of whether small increases in ambient moisture would amplify differences between ensembles, particularly those involving turnout gear and ballistic vests that restrict vapor transport. This design was expected to provide new insight into how clothing-imposed evaporative limitations interact with environmental humidity to drive physiological heat strain. Specifically, the comparison between 30% and 40% relative humidity allowed evaluation of whether observed differences in core temperature response was primarily driven by thermal resistance alone, or increasingly governed by evaporative bottlenecks as humidity increased. In this way, the protocol moved beyond extreme-condition testing and instead probed realistic but physiologically sensitive environments where small changes in humidity could disproportionately influence heat storage, offering practical relevance for firefighters and tactical operations conducted in warm, moderately humid climates.

50th percentile male and female population was modeled to represent the average population. The total simulation duration was 120 minutes, structured with alternating 20-minute walking periods at a metabolic rate of 3 METs and 20-minute rest periods at 1.1 METs. This work-rest cycle replicated realistic occupational activity patterns, allowing for systematic assessment of heat strain across gender and humidity conditions.

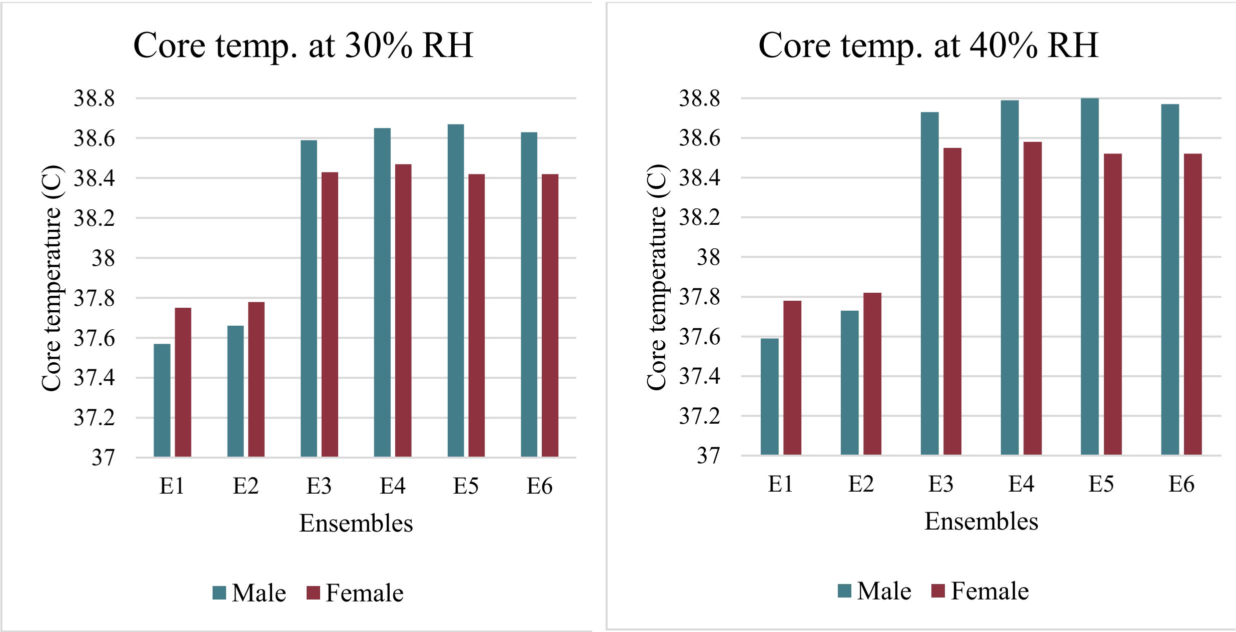


Figure 66. Core temperatures at 30% and 40% RH

When comparing the 30% and 40% RH datasets, the influence of humidity on gender-specific thermal responses becomes evident. At both humidity levels (Figure 66), females exhibited slightly higher core temperatures than males in lighter ensembles (E1-Station Uniform and E2- Station Uniform +Vest), reflecting reduced evaporative efficiency from garment fit and bust contour. However, in multilayered systems (E3-TS, E4-Covert, E5-Overt, E6-Hard Plates), males consistently surpassed females, with the disparity being more pronounced at 40% RH (+0.15-0.28 °C vs. +0.08-0.25 °C at 30% RH). This suggested that increasing humidity exacerbates the evaporative resistance penalty in males more than in females once vapor pathways are already constrained by heavy ensembles. Interestingly, female core temperatures plateaued across heavier PPE at both humidity levels (~38.4-38.6 °C), while male values continued to rise progressively. The data demonstrate that although females face a modest disadvantage in lighter clothing, males experience disproportionately greater heat strain under humid, and multilayered conditions, highlighting the combined effects of anatomy, clothing compression, and environmental vapor pressure on gender-specific thermal burden. This pattern reflects the interaction between anatomical differences, garment-body contact, and ambient vapor pressure. In heavier ensembles, more uniform geometry of male torso promotes greater and more continuous clothing compression, which restricts air exchange and moisture transport. As ambient humidity increases, the reduced vapor pressure gradient further limits sweat evaporation, leading to a disproportionate increase in heat storage in males. In contrast, localized contour-driven air exchange in females appears to partially offset evaporative limitations, resulting in a plateau in core temperature despite increasing ensemble complexity.

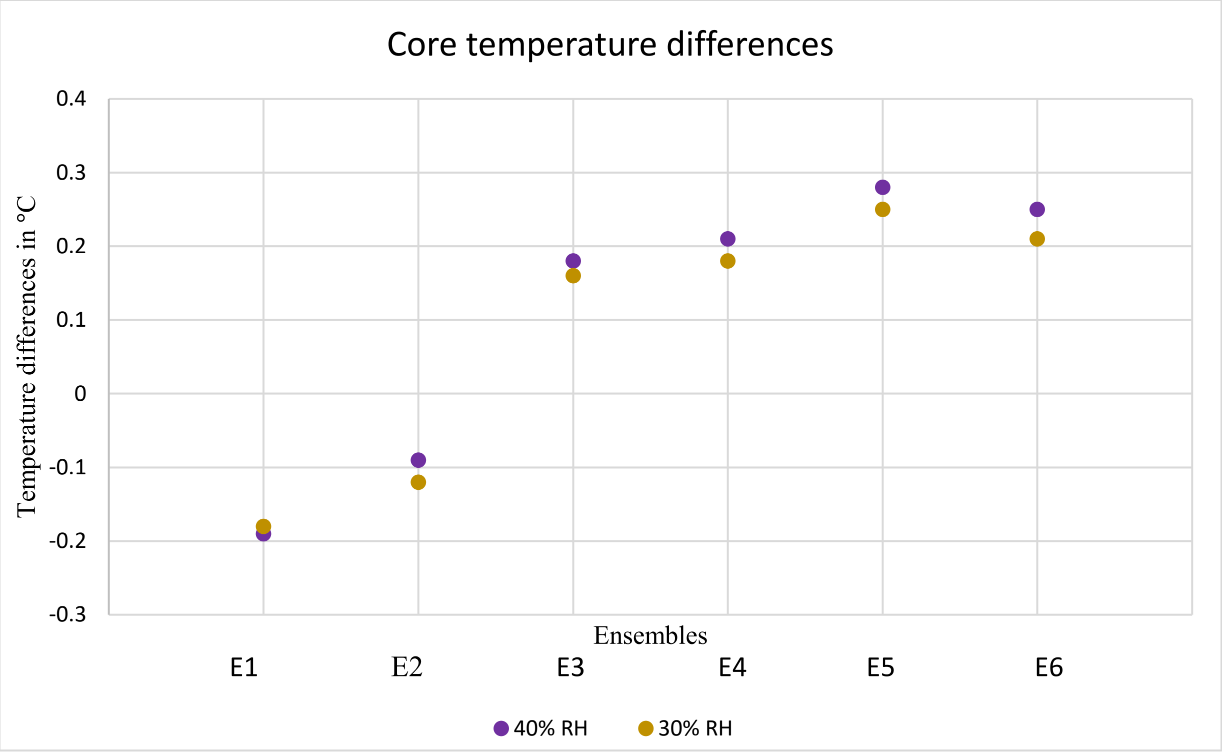


Figure 67. Core temp differences between male and female at different RH%

The plotted differences highlighted the dynamic shift in thermal burden between males and females as clothing complexity increases and relative humidity rises (Figure 67). Negative values while wearing E1 (Station Uniform) or donning the ballistic vest over station uniform (E2) conditions confirmed that females experienced higher core temperatures than males under light ensembles, but the positive inflection beginning with turnout suits showed a clear crossover, where males become more thermally burdened. The divergence between the 30% and 40% RH curves demonstrated that humidity amplifies this effect, with males consistently accruing an additional ~0.02-0.05 °C penalty under humid conditions once evaporative pathways were constrained. The peak differences observed in the E3 (turnout suit) and E4 (covert) ensembles suggest that multilayer configurations not only raise overall thermal strain but also exacerbate gender-specific disparities, underscoring the need to evaluate PPE design under combined clothing-environment interactions rather than isolated factors.

5.2.5 Effect of different environmental temperatures

The simulation was conducted with the ambient temperatures of 30°C & 32°C and relative humidity of 50%. The activity level was 3MET for 20 minutes walk and 20 minutes rest (1.1 MET) cycle, for a total of 120 minutes activity for the 50th percentile male and female. The graph (Fig 68) of core temperature differences between male and female showed that ensemble type affects gender-based thermal divergence, environmental temperature modulates these differences in a consistent manner.

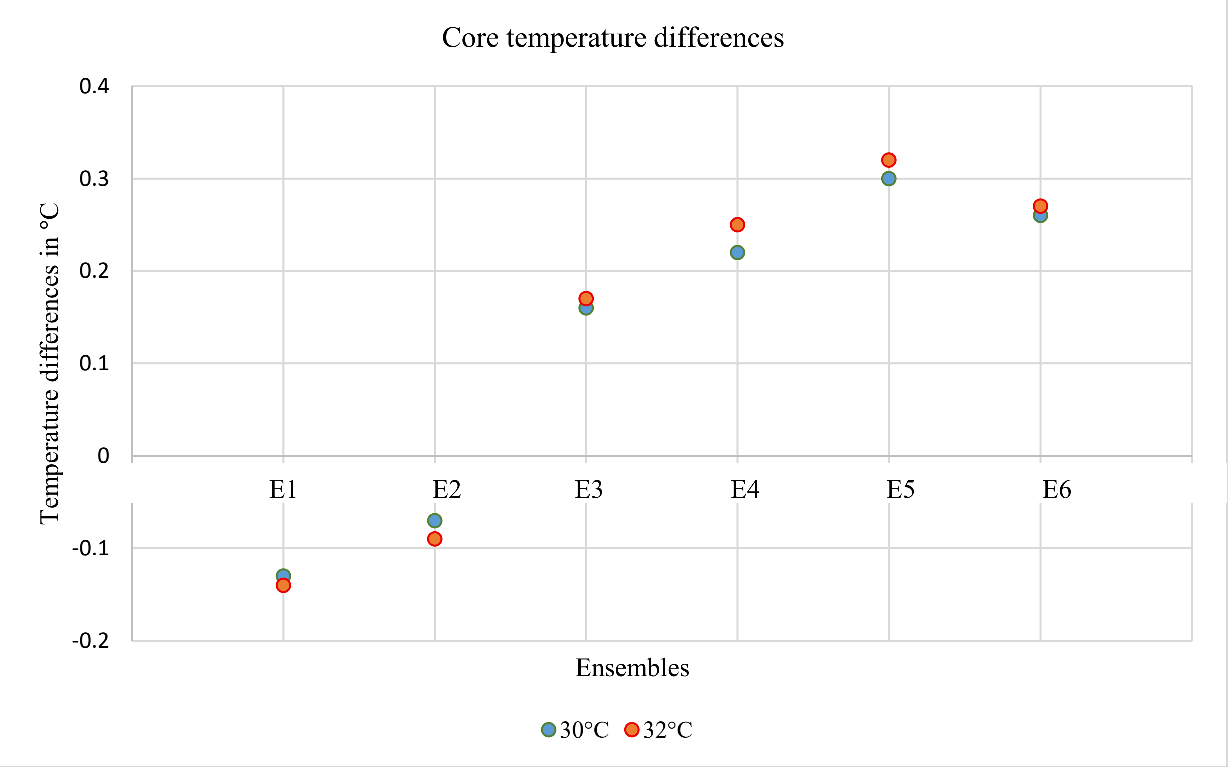


Figure 68. Core temp differences between male and female at different temperatures

In lighter ensembles (E1-E2), the differences were negative, meaning females maintained slightly higher core temperatures than males, likely due to their higher evaporative resistance and smaller torso surface area reducing vapor transport efficiency. When a turnout suit was added, this continued to show the dominant effect of the turnout suit. From E3 onward (turnout suit + ballistic ensembles), the difference shifts positive and steadily increased, peaking around E5 (~+0.30-0.32 °C), where males exhibited substantially higher core temperatures than females. This reversal reflected anatomical and fit-related factors: male torsos with flatter chest curvature create tighter contact with turnout and ballistic gear, limiting micro-ventilation and trapping heat, while the female torso shape allowed localized convective and evaporative channels that mitigated thermal rise despite higher intrinsic R_{et}.

When comparing the two environments, raising the air temperature from 30°C to 32°C amplified the magnitude of differences at both ends: female T_{re} was slightly higher than male in lighter ensembles, and males were even hotter relative to females in heavier ensembles. Although the absolute gender-based differences were modest (0.1-0.3°C), they were physiologically meaningful [193], as they could increase cardiovascular strain and shorten sustainable work time, particularly during high-intensity firefighting operations.

The observed differences in core temperature across ensemble configurations were physiologically meaningful, despite their modest absolute magnitude. Human thermoregulation operates within a narrow safety margin, and even small elevations in core temperature (≈0.2-0.3 °C) are known to accelerate heat storage, increase cardiovascular strain, and reduce tolerance time during sustained work, particularly in occupations such as firefighting where metabolic heat production is high and opportunities for heat dissipation are limited. The progressive increase in core temperature from lighter ensembles (E1-E2) to more thermally restrictive systems (E3-E6) indicated that ensemble-induced constraints on dry and evaporative heat loss translated directly into elevated internal heat strain.

5.2.6 Effect of different activity levels

Table 8 presented the calculated walking speeds required for male and female subjects to maintain a constant metabolic rate of 3 METs (≈174 W/m²) while carrying progressively heavier external loads at 35°C temperature and 30% RH. The goal of this analysis was to ensure equivalent metabolic workloads across genders despite physiological and anthropometric differences such as body mass and stature.

The 50th percentile male (78.5 kg, 1.77 m) and 50th percentile female (65 kg, 1.65 m) were selected from the TAITherm parameter to bear identical carried loads ranging from 3 kg to 20 kg, representing the increasing mass of protective ensembles (e.g., station uniform, ballistic vest, turnout gear). To maintain the same metabolic intensity of 3 MET, walking speed was adjusted slightly between genders. Because metabolic rate is a function of both body weight and movement speed, lighter individuals (in this case, females) must walk slightly faster than heavier individuals to expend the same energy per unit body surface area.

Table 10. Constant MET with varying walking speed

Subject	Weight (kg)	Load (kg)	Speed (km/hr)	Height (m)	MET
Male	78.5	3	**4.225**	1.77	**3.00**
Female	65	3	**4.41**	1.65	**3.00**

Table 8. (continued)

Subject	**Weight (kg)**	**Load (kg)**	**Speed (km/hr)**	**Height (m)**	**MET**
Male	78.5	7.2	**4.1**	1.77	**3.00**
Female	65	7.2	**4.25**	1.65	**3.00**
Male	78.5	8.32	**4.06**	1.77	**3.00**
Female	65	8.32	**4.21**	1.65	**3.00**
Male	78.5	12.5	**3.93**	1.77	**3.00**
Female	65	12.5	**4.04**	1.65	**3.00**
Male	78.5	20	**3.69**	1.77	**3.00**
Female	65	20	**3.73**	1.65	**3.00**

Table 9 summarized the walking speeds, body weights, and corresponding metabolic equivalents (METs) for male and female subjects under different load conditions, with walking speed held constant for both genders. The objective of this analysis was to isolate the physiological effects of body size and mass on metabolic intensity during equivalent external workloads, simulating conditions in which both male and female firefighters perform the same task at the same pace.

Table 11. Individual constant walking speed for each ensemble

Subject	**Weight (kg)**	**Load (kg)**	**Speed (km/hr)**	Height (m)	**MET**
Male	78.5	3	**4.225**	1.77	**3.00**
Female	65	3	**4.225**	1.65	**2.85**
Male	78.5	7.2	**4.1**	1.77	**3.00**
Female	65	7.2	**4.1**	1.65	**2.87**
Male	78.5	8.32	**4.06**	1.77	**3.00**
Female	65	8.32	**4.06**	1.65	**2.88**
Male	78.5	12.5	**3.93**	1.77	**3.00**
Female	65	12.5	**3.93**	1.65	**2.90**
Male	78.5	20	**3.69**	1.77	**3.00**
Female	65	20	**3.69**	1.65	**2.97**

In this scenario, the male subject (78.5 kg, 1.77 m) maintained a constant metabolic intensity of 3.00 METs across all loads (3 kg to 20 kg). The female subject (65 kg, 1.65 m), walking at the same speeds as the male (1.17-1.02 m/s depending on load), exhibited slightly lower MET values ranging from 2.85 to 2.97 METs. This small deviation indicates that, at equal walking velocities, the lighter female subject expended less energy per unit body surface area, as total metabolic rate scaled with body mass and mechanical work performed.

As the load increased from 3 kg to 20 kg, both subjects showed the expected decrease in walking speed to maintain realistic firefighter movement patterns under heavier ensembles. However, since male metabolic rate was fixed, the constant-speed design caused a gender-based divergence in relative workload: males sustained the target 3 MET activity level, while females operated slightly below it. This difference was physiologically meaningful because it mirrored field conditions in which firefighters of different body masses performed identical physical tasks, resulting in varying relative energy demands and heat production rates.

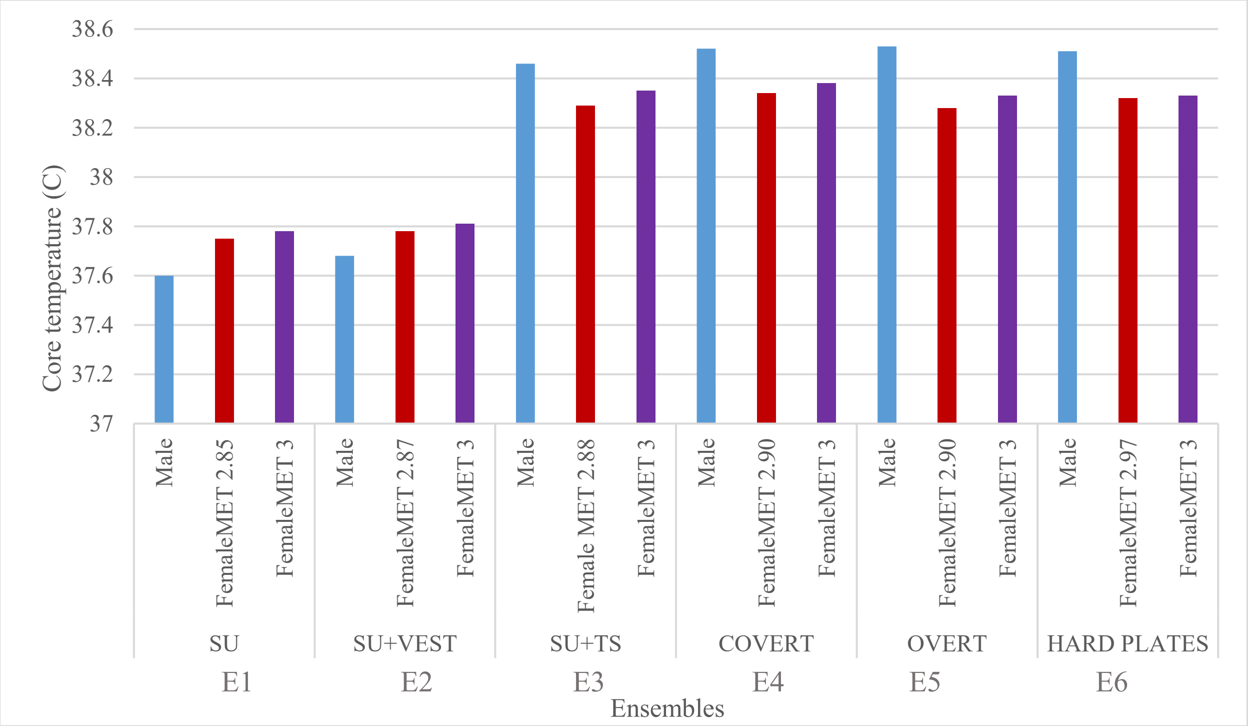


Figure 69. Core temperature at different MET

In Figure 69, the plotted data illustrated the thermophysiological effect of metabolic intensity differences between males and females across six ensembles: E1-station uniform (SU), E2-station uniform with vest (SU + VEST), E3-station uniform plus turnout suit (SU + TS), E4-covert vest, E5-overt vest, and E6-vest with hard plates under an environmental condition of 35°C, 30% RH, 15 mins rest (1.1 MET) and 25 mins walk (2.85-3 MET). When both genders were simulated at 3 MET, the female core temperature (T_{re}) equaled or slightly exceeded the male T_{re} across E1-E2. However, after adding turnout suit and ballistic vests, male T_{re} exceeded female T_{re} suggesting a plateau where the body approaches a constrained heat-balance regime; additional layers of ballistic vest incrementally worsened heat dissipation, but the largest degradation occurred once the protective turnout barrier was introduced. One plausible interpretation is that in heavy, encapsulating ensembles, differences in absolute heat production and heat storage capacity (and potentially garment-body air-gap distribution and ventilation pathways) could shift which body model accumulated heat more rapidly. Meanwhile, in lighter clothing where evaporative pathways were less restricted, smaller differences in heat transfer and thermoregulatory set-points could become more visible, yielding slightly higher core temperatures in the female conditions.

In the constant-speed trials where males maintained 3 MET and female MET values ranged from 2.85 to 2.97, the female core temperatures dropped modestly (≈ 0.1-0.2 °C) relative to the matched 3 MET condition. This outcome confirmed that even small reductions in metabolic rate (heat production) can lower thermoregulatory strain when external insulation (from vests or turnout suits) remains unchanged, which was entirely expected based on fundamental heat-balance principle. For instance, in the station uniform (SU), the male T_{re} was

~37.6 °C while the female T_{re} decreased to ~37.7 °C at 2.85 MET compared to ~37.8 °C at 3 MET. As clothing thermal and evaporative resistance increased (e.g., E3-E6), both genders showed progressive T_{re} elevation, but the male values peaked higher (~38.5 °C) because males produced more metabolic heat at the fixed 3 MET intensity. Females working at slightly lower METs (~2.9-2.97) maintained T_{re} below 38.3 °C, indicating that the difference in metabolic heat generation offset the disadvantages of lower evaporative efficiency. Overall, the data revealed two complementary findings: (a) at equal METs (3.0), females exhibit greater thermal strain in E1-E2, emphasizing the role of physiological and anatomical factors (lower sweat rate, body morphology). Metabolic heat production scales primarily with body mass, because oxygen consumption and energy expenditure were mass-dependent. In contrast, the body's capacity to dissipate heat through convection, radiation, and evaporation scaled more closely with body surface area. These two quantities did not increase proportionally, and their relationship was nonlinear, such that individuals with smaller body mass and surface area often produced more heat per unit surface area at the same relative metabolic intensity (METs). Consequently, for a given MET level, females who typically had lower body mass, but also lower body surface area experience a higher ratio of metabolic heat production to available heat-dissipating area. This unfavorable heat production to surface area ratio increased reliance on evaporative cooling and elevates susceptibility to heat storage when evaporative pathways are constrained by protective clothing [194]. Thus, the greater thermal strain observed in females at matched METs compared to adjusted constant speed for each ensemble MET for female was not unexpected but increased from intrinsic biophysical scaling differences between heat generation and heat loss, compounded by ensemble-imposed limitations on evaporation and (b) at equal speeds (hence lower female METs), males experienced greater heat storage, underscoring that absolute metabolic rate not just clothing insulation drove core temperature rise.

From a critical standpoint, the figure also showed that once protective systems pushed the wearer into the ~38.3-38.6 °C range, additional armor configurations (E4-E6) offered diminishing "separation" in core temperature relative to the turnout baseline (E3). This had practical significance: it suggested that managing heat strain may require targeting the primary bottleneck introduced at the turnout stage (ventilation, moisture transport, and evaporative capacity at the torso), rather than expecting large improvements from small changes among armored variants alone. At the same time, interpretation must remain cautious because the plotted outcomes depended on how metabolic rate was assigned (male vs female MET conditions) and on model assumptions governing sweat evaporation and clothing resistances; therefore, conclusions should emphasize the robust, high-signal result (turnout gear drove the major rise in core temperature) while treating smaller gender and workload differences as conditional on the chosen workload normalization and garment-body interaction assumptions.

Thus, this dual-table and graph comparison indicated how metabolic scaling interacted with gender-specific physiology and ensemble insulation to govern thermal strain outcomes. The results validated the importance of metabolic rate normalization (same workload) when comparing thermophysiological performance between male and female firefighters under identical PPE configurations.

5.2.7 Effect of constant walking speed with various load carriage on male and female

Table 12. Constant walking speed for all ensembles

Subject	**Weight (kg)**	**Load (kg)**	**Speed (km/hr)**	**Speed (m/s)**	**Height (m)**	**MET**
Male	78.5	3	**4.225**	1.1736205	1.77	**3.00**
Female	65	3	**4.225**	1.1736205	1.65	**2.85**
Male	78.5	7.2	**4.225**	1.138898	1.77	**3.12**
Female	65	7.2	**4.225**	1.138898	1.65	**2.98**
Male	78.5	8.32	**4.225**	1.1277868	1.77	**3.15**
Female	65	8.32	**4.225**	1.1277868	1.65	**3.02**
Male	78.5	12.5	**4.225**	1.0916754	1.77	**3.27**
Female	65	12.5	**4.225**	1.0916754	1.65	**3.17**
Male	78.5	20	**4.225**	1.0250082	1.77	**3.52**
Female	65	20	**4.225**	1.0250082	1.65	**3.48**

Table 10 presented the calculated metabolic equivalents (METs) for male and female subjects walking at a constant speed of 4.225 km/h (1.17 m/s) while carrying progressive external loads ranging from 3 kg to 20 kg on a 1% grade terrain. This analysis was conducted to quantify how body mass, load, and metabolic scaling interact when both genders perform identical tasks under equal environmental and mechanical conditions

The male subject (78.5 kg weight, 1.77 m height) maintained higher absolute energy expenditure (MET) values across all load conditions, increasing from 3.00 MET at a 3 kg load to 3.52 MET at a 20 kg load. In contrast, the female subject (65 kg weight, 1.65 m height) exhibited slightly lower METs under the same conditions, rising from 2.85 MET to 3.48 MET as load increased. This small but consistent difference was observed because metabolic cost scaled with body weight and total mass (body + load) where heavier individuals spent more energy to move at the same relative speed, especially when carrying identical external loads. As load increased from 3 kg to 20 kg, both males and females experienced a proportional increase in metabolic intensity due to the additional muscular work required to overcome gravitational and inertial forces. The nearly parallel increase in METs for both genders indicated that the effect of added load on energy cost was similar in pattern but differed in magnitude due to total body mass.

Overall, Table 10 highlighted that when speed was constant, metabolic workload diverges by gender-males, being heavier, operate at a higher absolute energy expenditure than females. This distinction was crucial when comparing physiological strain and thermal response between male and female firefighters for interpreting physiological strain, because equal task speed did not translate to equal internal heat production or equal thermal burden when comparisons were made on an absolute basis (W). Consequently, direct male vs female comparisons based solely on speed or task description could be misleading, as females may have experienced greater relative heat strain per unit body mass or surface area, even when absolute metabolic rates were lower. These highlighted why gender-specific analyses were necessary when evaluating firefighter PPE performance and heat strain risk.

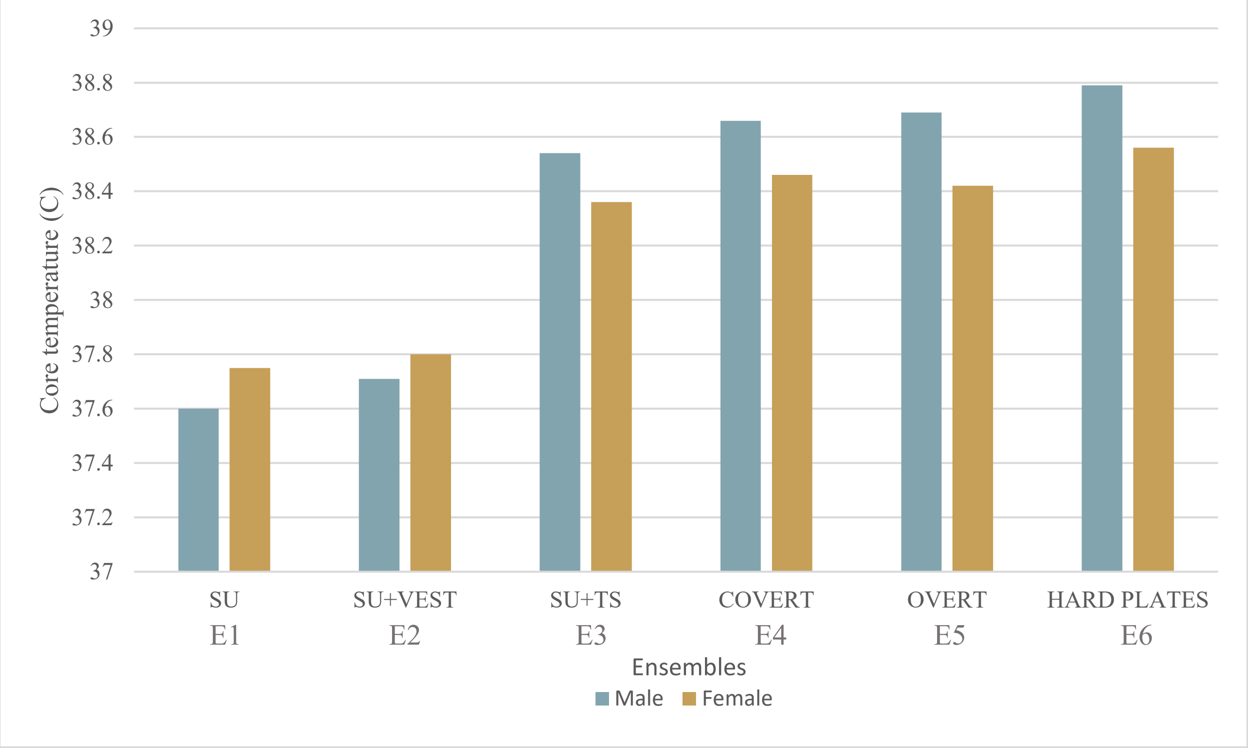


Figure 70. Core temperature of male and female with constant walking speed

Figure 70 illustrated the predicted core temperature (T_{re}) of male and female subjects wearing six ensemble configurations: E1-Station Uniform (SU), E2-Station Uniform + Vest (SU + VEST), E-3Station Uniform + Turnout Suit (SU + TS), E4-Covert Vest, E5-Overt Vest, and E6- Hard Plates while walking at a constant speed of 4.225 km/h on a 1% grade terrain under an environmental condition of 35°C, 30% RH, 15 mins rest (1.1 MET) and 25 mins walk (3-3.52 MET) . Corresponding metabolic equivalent (MET) values from Table 7 showed that, although both genders walked at identical speeds, males consistently exhibited higher metabolic intensity (3.00-3.52 MET) than females (2.85-3.48 MET) because of greater total body and load mass and higher absolute energy expenditure.

This difference in metabolic heat production explains the observed pattern of higher core temperatures in males across all ensembles except for E1-E2. As load increased, both male and female T_{re} values increased progressively, reflecting greater thermal insulation (R_t) and evaporative resistance (R_{et}) imposed by the multi-layered protective systems. However, males reached consistently higher T_{re} peaks from ~38.5 °C in turnout suit to ~38.8 °C with hard plates compared to females, who ranged from ~37.3 °C to ~38.5 °C. Higher male core temperatures directly corresponded to greater metabolic heat production at the same walking pace.

In contrast, females exhibited slightly lower core temperatures under each ensemble from E3-E6 despite their less efficient evaporative cooling physiology. This is because their lower MET values (by ≈ 0.1-0.2 units) resulted in proportionally less internal heat production. The physiological implication was that, during activities at equivalent speed, body mass became the dominant determinant of total metabolic load, outweighing the minor differences in thermoregulation efficiency between genders.

Nonetheless, as ensembles became more restrictive (e.g., E3-E6), both genders approached the upper physiological safety limit (~38.5-38.8 °C), highlighting that increasing load and insulation can induce critical heat strain even at moderate work intensities. The trend underscores how, in field conditions, male firefighters may experience higher core temperatures when performing identical-paced tasks, whereas female firefighters may appear less heat-strained only because their metabolic workload is lower at the same speed not because their thermal tolerance or PPE performance differs.

5.2.8 Effect of extreme height and weight differences

The simulation was conducted at an ambient temperature of 30°C and a relative humidity of 50%. The activity level was 5MET, with 20 minutes walk and 20 minutes rest (1.1 MET) cycle where total activity time was 120 minutes for the 5th and 95th percentile male and female (see Appendix E for height and weight) wearing turnout suit with overt ballistic vest. Across the simulated exposure, core temperature increased progressively for all anthropometric percentiles and genders (Figure 71), with distinct and systematic differences emerging as a function of body size and gender. Early in the exposure period (0-30 min), core temperature responses were similar across all groups, indicating an initial phase of compensated thermoregulation in which heat production and heat dissipation remained largely balanced. However, as exposure duration increased with activity level, clear stratification emerged between individuals at the 5th and 95th percentile, with larger-bodied subjects exhibiting higher rates of heat storage and greater absolute increase in core temperature.

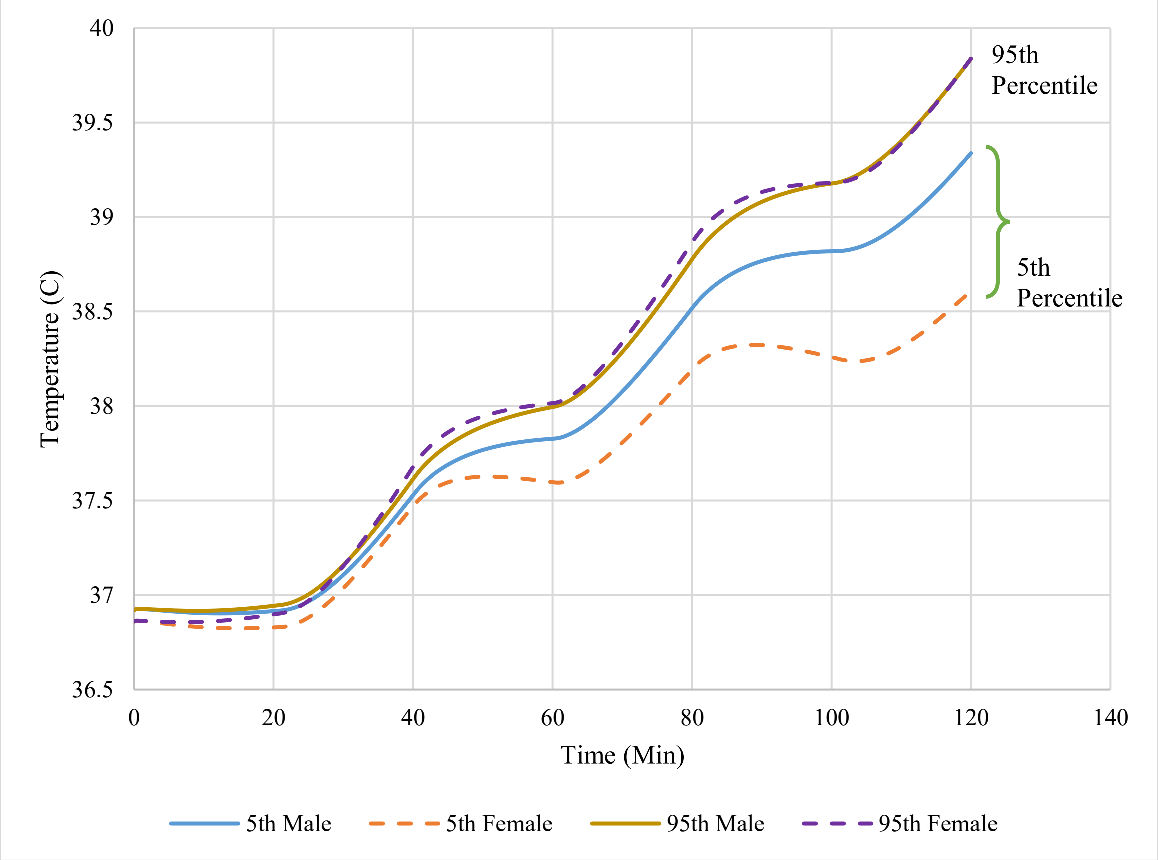


Figure 71. Core temperature of the 5th and 95th percentile males and females

For the 5th percentile female data, core temperatures remained consistently lower than those of males throughout the exposure, with the divergence becoming more pronounced after approximately 60 minutes. This pattern indicated a relative thermophysiological advantage for smaller-bodied females, characterized by slower heat accumulation and delayed progression toward critical core temperature thresholds. These differences were consistent with established mechanisms, including lower absolute metabolic heat production, a higher surface-area-to-mass ratio, and more effective heat dissipation under the modeled environmental and clothing conditions. As a result, the 5th percentile female maintained a greater margin of thermal safety throughout the exposure compared to the 5th percentile male.

In contrast, at the 95th percentile level, the male and female core temperature trajectories converged closely, particularly during the latter half of the exposure (i.e., 100-120 mins). Both genders showed rapid, and sustained increases in core temperature, approaching levels associated with high physiological strain by the end of the protocol. The minimal separation between male and female responses at the 95th percentile suggested that body size and thermal mass exerted a dominant influence on thermoregulatory capacity under these conditions, effectively diminishing gender-related differences. At higher body masses, reduced surface-area-to-mass ratio, greater absolute metabolic heat production, and increased clothing-related resistance collectively constrain heat dissipation, resulting in comparable levels of thermal strain across genders of different height and weight combinations.

In summary, in the effect of gender (5.2.1) and effect of rest time (5.2.2) sections, it was evident that female mean skin temperature, core temperature, and cardiac output were always lower in females than males. On average, females exhibit lower mean skin temperatures (T_{sk}) than males, a difference arising from distinct physiological and anatomical characteristics that influence thermoregulation. Males typically possess a higher proportion of lean muscle mass compared to females, resulting in greater metabolic heat production during both rest and activity. Because skeletal muscle is the primary site of thermogenesis, the lower relative muscle mass in females leads to reduced endogenous heat generation and consequently a lower steady-state skin temperature under equivalent environmental or metabolic conditions [183]. Females generally have a higher total body fat percentage and a more peripheral pattern of adipose distribution particularly around the thighs, hips, and subcutaneous torso regions. Adipose tissue acts as an insulative layer that impedes conductive and convective heat transfer from core to skin. This additional insulation reduces heat flux toward the body surface, thereby lowering mean skin temperature, especially in regions of thicker subcutaneous fat [184]. Endocrine factors further modulate female thermoregulation. Estrogen promotes peripheral vasoconstriction, reducing cutaneous blood flow and thereby diminishing the convective transport of metabolic heat from the core to the skin surface [185]. This hormonal vasoconstrictive effect is cyclically enhanced during certain phases of the menstrual cycle, leading to transient reductions in skin perfusion and surface temperature. Progesterone can also elevate the thermoregulatory set point, shifting the threshold for vasodilation to higher core temperatures [185]. Collectively, these hormonal dynamics contribute to persistently lower T_{sk} values observed in females under comparable thermal loads.

Adult males generally exhibit slightly higher core body temperatures than adult females, a disparity that can be attributed to a confluence of physiological and anatomical factors influencing heat production, storage, and dissipation. Because males typically have greater body mass relative to surface area (i.e., a lower surface-area-to-volume ratio) compared to females, the rate of heat dissipation per unit of produced heat is reduced. A smaller relative surface area limits convective and radiative heat loss, thereby elevating steady-state core temperature under equivalent metabolic loads or ambient conditions [186]. Also, males generally possess a higher proportion of lean (fat-free) mass particularly skeletal muscle which is highly metabolically active even at rest. This augmented lean-mass component increases basal metabolic heat production, thus contributing to a higher internal heat load and elevating core temperature in the absence of compensatory cooling [187]. Emerging evidence suggests that central thermoregulatory control mechanisms including the Hypothalamus and pre-optic regulatory nuclei may differ between genders. These central circuits govern heat production (thermogenesis), basal metabolic rate modulation and heat loss effectors (e.g., vasodilation, sweating). The hypothesis is that a slightly higher baseline set-point or reduced heat-loss sensitivity in males may further contribute to elevated core temperatures under certain conditions [183].

On average, females exhibit lower cardiac output (CO) than males under resting and exercising conditions. This difference arises from a combination of structural, physiological, and metabolic factors that collectively influence cardiac performance and systemic blood flow. Female hearts are typically smaller than male hearts by approximately 20–25% after adjusting for body surface area. Morphological studies using cardiac magnetic resonance imaging (MRI) and echocardiography show that women possess smaller left ventricular (LV) end-diastolic volumes, thinner ventricular walls, and reduced LV mass compared to men of similar age and race [195]. These structural differences constrain the volume of blood that can be ejected per beat, thereby limiting stroke volume and total cardiac output even when heart rate is equivalent. Independent of body size, females have smaller ventricular chambers and narrower aortic diameters and lengths, reducing total vascular capacitance and limiting blood flow capacity

[188]. As a result, stroke volume (SV) the primary determinant of cardiac output is consistently lower in women, averaging approximately 20-25% less than that observed in men. This reduction is not merely proportional to body size but reflects intrinsic gender differences in myocardial geometry and arterial compliance. Cardiac output is tightly coupled to tissue metabolic demand, since it governs systemic oxygen delivery. Because females generally have a lower resting metabolic rate attributable to a lower proportion of metabolically active lean mass overall oxygen consumption ($\dot{V}O_2$) and, consequently, cardiac output requirements are reduced [188]. This physiological efficiency aligns with lower baseline sympathetic activation and attenuated circulatory drive, resulting in reduced CO at rest and during submaximal workloads.

CHAPTER 6

CONCLUSION

This study integrated thermal manikin experimentation and thermophysiological modeling to evaluate how the inclusion of ballistic protection alters the thermal, evaporative, and physiological performance of firefighter protective ensembles. By employing both Newton (male) and Liz (female) manikins, the investigation provided quantitative insight into how gender-specific body morphology and garment fit modulate heat and moisture transfer within complex multi-layered protective systems.

Manikin-based measurements revealed that the addition of ballistic vests particularly when combined with turnout gear significantly increased thermal resistance (R_t) and evaporative resistance (R_{et}) while reducing predicted total heat loss (THL) across all ensembles. The upper torso consistently emerged as the critical limiting region for heat dissipation, where trapped air layers, impermeable materials, reduced ventilation collectively heightened local thermal burden. Although whole ensemble-level differences between both genders were modest, zone-by-zone torso analyses exposed distinctive anatomical effects: the male's flatter chest geometry facilitated tighter garment fit and less ventilation in the back region, leading to higher local R_t and R_{et}, whereas the female's contoured torso introduced small ventilation pathways that slightly improved convective and evaporative exchange.

These findings align with and extend existing research on heat strain in encapsulating protective clothing, which has consistently shown that once evaporative resistance is elevated, thermoregulation becomes increasingly constrained and small changes in design or environment can lead to disproportionate physiological consequences. Prior studies of firefighter PPE and ballistic armor have demonstrated that added layers increase insulation and vapor resistance but have rarely examined how these effects interact with turnout gear or differ by gender-specific anatomy. The present work builds on this knowledge by demonstrating that, although ballistic vests measurably increase thermal burden over station wear, their incremental effect becomes comparatively small once the turnout ensemble establishes a dominant evaporative bottleneck. Importantly, the study shows that anatomical fit and body morphology modulate how this burden is distributed, particularly at the torso, providing mechanistic insight that is largely absent from earlier ensemble-level evaluations.

When sweating manikin data were incorporated into TAITherm™ human thermal modeling, the physiological implications of these material and anatomical differences became evident. Under equivalent metabolic intensities (3 MET), female models exhibited greater thermal strain, characterized by higher predicted core and skin temperatures, likely due to lower sweat rates, smaller body-surface-area-to-mass ratios, and higher subcutaneous insulation. However, when walking speed was held constant resulting in lower female METs (2.85-3.48) compared with male METs (3.00-3.52) male models displayed higher core temperatures, reflecting their greater metabolic heat production at identical pace and load. These findings showed that metabolic scaling (same MET), not merely clothing design, governs much of the observed gender-based thermal response. Nonetheless, female physiology remains at higher relative risk of heat stress under similar metabolic loads because of reduced evaporative efficiency and cardiovascular reserve. The findings in the effect of extreme height and weight of male and female demonstrate that anthropometric variability plays a critical role in shaping core temperature responses under identical environmental and clothing conditions. Smaller-bodied individuals, particularly females at the 5th percentile, experience delayed heat storage and lower peak core temperatures, whereas larger-bodied individuals at the 95th percentile exhibit accelerated heat accumulation and elevated thermal risk regardless of gender. These results underscore the limitations of relying on average-body or gender-only models for heat strain assessment and highlight the necessity of incorporating body size and percentile-based considerations into thermophysiological modeling, work–rest recommendations, and protective ensemble evaluation. Future work should expand beyond percentile-based simulations to include experimental validation with human subjects representing a wider range of anthropometric profiles. While modeling provides critical insight into thermophysiological trends, controlled human trials would allow verification of predicted differences in core temperature trajectories, sweating efficiency, and cardiovascular strain across body sizes and genders under realistic operational conditions.

Collectively, the results show that ballistic vests substantially increase thermal burden in firefighter ensembles worn over station uniform. However, because of the profound effect of the turnout thermal resistance and air layer, the impact of the ballistic vest is really small, whether it is worn under or over the turnout suit.

This study advances current knowledge by demonstrating that heat strain performance cannot be evaluated solely on material properties, but must also consider anatomical fit, body morphology, and gender-specific thermophysiological responses. These findings indicate the need for ergonomically and thermally optimized vest designs, particularly tailored for female firefighters whose gear is often patterned after male anthropometry such as ergonomically and thermally optimized vest designs that is tailored to female firefighters, whose equipment is frequently derived from male anthropometric patterns. Beneficial design modifications may include female-specific torso shaping to reduce localized compression, zoned compliance to improve pressure distribution across the chest, and ventilation strategies aligned with female anatomical contours to enhance moisture removal. Customized adjustability of the chest and waist regions may further improve fit stability while limiting evaporative resistance. Together, these changes have the potential to reduce heat storage in multilayered PPE systems and mitigate gender-specific heat strain without compromising protective performance.

From a standards perspective, the results underscore the necessity of integrating thermal comfort metrics (R_t, R_{et}, THL) and physiological modeling outcomes into future PPE evaluation protocols, complementing existing ballistic and flame protection criteria. This integrated framework bridging experimental data, digital simulation, and gender-aware analysis provides a scientific foundation for developing next-generation firefighter ensembles that maintain ballistic integrity while minimizing heat strain, thereby enhancing safety, endurance, and operational performance across diverse responder populations.

From a broader operational perspective, these results suggest that ballistic vests are most likely to exacerbate heat strain when environmental and task conditions already limit heat dissipation. Specifically, ballistic protection becomes increasingly problematic in warm or moderately humid environments where dry heat loss is minimal, and evaporation is the primary cooling pathway; during prolonged or repeated work–rest cycles where incomplete recovery allows heat to accumulate; and when vest designs restrict ventilation in critical torso regions. Under such conditions, even modest increases in evaporative resistance can accelerate the transition toward uncompensable heat stress. These findings support practical warnings for deployment: stacking ballistic vests with turnout gear during extended operations should be accompanied by shortened work cycles, earlier rehabilitation, and careful monitoring of heat strain, particularly for female firefighters who may experience higher relative physiological burden at equivalent metabolic intensities. The findings of this study demonstrate that compliance with existing ballistic and flame protection requirements alone is insufficient to ensure safe thermophysiological performance of firefighter PPE. Measured thermal insulation (R_t), evaporative resistance (R_{et}), and total heat loss (THL), together with physiological modeling outcomes, show that heat strain varies substantially across PPE configurations, environmental humidity levels, and wearer anatomy. In particular, multilayered systems incorporating ballistic vests can impose a disproportionate heat burden that is not captured by current certification criteria. From a standards perspective, these results support the inclusion of thermal performance metrics as a routine component of PPE evaluation. Reporting R_t, R_{et}, and THL for complete worn systems rather than individual materials would allow meaningful comparison among PPE options and provide agencies with actionable information during procurement. Establishing performance ranges or threshold values for evaporative resistance or heat loss would further help identify configurations that may present elevated heat-strain risk, especially during prolonged or high-intensity operations. The study also highlights the need for anthropometry-aware evaluation pathways within standards. Identical PPE configurations produced different thermophysiological responses in male and female firefighters, indicating that fit, body geometry, and garment compression influence heat dissipation. Standards and selection guidelines should therefore require evaluation using both male and female body representations or require manufacturers to demonstrate that design performance is maintained across a defined range of body shapes and sizes. This approach would reduce unintended bias toward male-based designs and improve thermal safety for a broader responder population. Validated thermophysiological modeling offers a practical and scalable tool to support these goals. When anchored to experimental measurements, modeling can assess heat strain under combinations of workload, environment, and PPE that are difficult to test experimentally. Allowing such models as supplementary compliance or screening methods would enable standards bodies and manufacturers to identify high-risk designs early and evaluate design modifications without compromising protective integrity. Finally, the results emphasize that thermal performance data should inform not only about certification but also PPE selection and deployment guidelines. Departments would benefit from guidance that links thermal burden to expected operational duration, environmental conditions, and task intensity. Incorporating thermal metrics into selection frameworks would allow agencies to choose PPE systems that balance protection with heat-strain risk, improving firefighter safety, endurance, and operational effectiveness across diverse response scenarios.

Building on these findings, several directions are recommended to advance the understanding of heat strain and protective performance in integrated firefighter ballistic ensembles. Future studies should validate manikin and simulation outcomes with controlled human subject trials, incorporating wearable physiological sensors to capture dynamic variables such as heart rate, sweat rate, and core temperature during realistic firefighting and rescue tasks. These data would enable calibration of simulation models to individual thermoregulatory variability and improve predictive accuracy.

The present work focused on moderate heat and relative humidity. Future investigations should examine extreme thermal environments, variable humidity, and prolonged work-rest cycles that mimic real deployment conditions. Integrating solar radiation, wind, and hydration status will provide a more holistic picture of environmental heat stress.

Research should also explore ventilated ballistic panel designs, phase-change materials, and smart textiles that enhance evaporative efficiency without compromising ballistic integrity. Computational optimization using multi-physics modeling could identify optimal trade-offs between protection, weight, and thermal comfort.

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Finally, it is always our great hope that the findings of this study may contribute to the safety and health of firefighters.

APPENDICES

Appendix A

Survey Questions in Chapter 3

1. In which region of the United States do you work?
2. Please choose the answer that best describes the community your department serves.
3. What position below best describes your current job position?
4. Are you currently a Career or Volunteer Firefighter?
5. How many years of experience do you have working within the fire service?
6. What configuration did you wear your ballistic protective vest during these situation(s)? (select all that apply)
7. During the scenario(s) you identified here, what Ballistic protection did you wear?
8. Please select all the Ballistic Protective Equipment currently owned or in-use by your department.
9. Is the ballistic equipment individually issued or is it a shared resource?
10. For which scenarios listed below have you received Ballistic Protective Equipment training?
11. For which scenario(s) listed below have you personally worn Ballistic Protective Equipment?
12. How many times have you worn your ballistic equipment in these situations?

Appendix B

Q & A (Chapter 3)

The discussion included some questions and answers relevant to ballistic vests for firefighters are as follows:

1. Researcher: What are the considerations that should be prioritized to purchase a ballistic vest for firefighters?

Manufacturer: *I think the wearability of the ballistic vest with firefighter turnout gear should be the top priority. As we know, firefighters wear helmets and self-contained breathing apparatus (SCBA). Ballistic vests should be interoperable with them.*

2. Researcher: How different are the ballistic vests sold to firefighters from law-enforcement (LE) officers?

Manufacturer: *In the late 80's, first responders wore covert ballistic vests unless there was a SWAT team. Now overt or blends into uniform ballistic vest is preferred. Ballistic vests are new to the Fire Dept. The main difference between law enforcement and non-law enforcement officers is in movement patterns. The profile of the ballistic vests should be cut differently.*

For the LE officers, there are always custom-made ballistic vests, but this is not the scenario for the first responders. There is one vest per truck/ one size fits "most" for the first responders. The sizing is done based on middle 80% body type that fits well because of low budget.

Correct solution: In this situation, if custom made ballistic vests are not economically feasible, it is encouraged to have at least two sizes of ballistic vests: one-S/M & another- L/XL to obtain better fit.

3. Researcher: Are there any details in the ballistic vests for firefighters that are different than usual?

Manufacturer: *There are different movement patterns for LE and first responders. LE officers have very specific or less movements than the first responders. Neckline and armhole are rectangle in shape for fire or EMS (not best fit but easy to make panels because of the straight cut) and round for LE officers to provide max coverage.*

4. Researcher: What are the threat levels and configurations of existing ballistic vests for the first responders?

Manufacturer: *Soft ballistic vest- IIIA (handgun-9mm ammunition) NIJ certified for firefighters/EMS people as a foundation of personal protective equipment. They may carry rifle plates in front and back for extra protection with Level IIIA in case of emergencies. There might be side panels too that are stab resistant. Most of the vests are adjustable. The vests are not flame-resistant though and they are not NFPA certified.*

5. Researcher: What are the current gaps you think should improve in terms of ballistic vests for first responders and EMS personnel?

Manufacturer: Ballistic vests should be an everyday wear vest. Current vests are bulky, hinder mobility, and are costly. It should be lighter in weight and provide a more custom fit.

Appendix C

Male clothing area factor:

Abbreviation	Ensembles	Total wt (kg)	F_{cl}
E1	Station Uniform (100% cotton t-shirt, dress pants, boxershorts, socks, station boots)	3	1.22

E2	Station Uniform + Ballistic Vest IIIA Overt (100% cotton t-shirt, dress pants, boxershorts, socks, station boots, ballistic vest IIIA)	7.2	1.26
E3	Station Uniform + Turnout suit (100% cotton t-shirt, dress pants, boxershorts, socks, turnout suit over station uniform, turnout boots)	8.32	1.53
E4	Station Uniform + Turnout suit + Ballistic Vest IIIA Covert (100% cotton t-shirt, dress pants, boxershorts, socks, turnout suit, turnout boots, ballistic vest IIIA over the turnout suit)	12.5	1.63
E5	Station Uniform + Ballistic Vest IIIA Overt + Turnout suit (100% cotton t-shirt, dress pants, boxershorts, socks, turnout suit, turnout boots, ballistic vest IIIA under the turnout suit)	12.5	1.60
E6	Station Uniform + Turnout suit + Ballistic Vest IV (with hard plates-front & back) Overt (100% cotton t-shirt, dress pants, boxershorts, socks, turnout suit, turnout boots, ballistic vest IV over the turnout suit)	20	1.61

Female clothing area factor:

Abbreviation	Ensembles	Total wt (kg)	F_{cl}
E1	Station Uniform (100% cotton t-shirt, dress pants, sports bra, panties, socks, station boots)	3	1.15
E2	Station Uniform + Ballistic Vest IIIA Overt (100% cotton t-shirt, dress pants, sports bra, panties, socks, station boots, ballistic vest IIIA)	7.2	1.21

E3	Station Uniform + Turnout suit (100% cotton t-shirt, dress pants, sports bra, panties, socks, turnout suit over station uniform, turnout boots)	8.32	1.44
E4	Station Uniform + Turnout suit + Ballistic Vest IIIA Covert (100% cotton t-shirt, dress pants, sports bra, panties, socks, turnout suit, turnout boots, ballistic vest IIIA over the turnout suit)	12.5	1.48
E5	Station Uniform + Ballistic Vest IIIA Overt + Turnout suit (100% cotton t-shirt, dress pants, sports bra, panties, socks, turnout suit, turnout boots, ballistic vest IIIA under the turnout suit)	12.5	1.53
E6	Station Uniform + Turnout suit + Ballistic Vest IV (with hard plates-front & back) Overt (100% cotton t-shirt, dress pants, sports bra, panties, socks, turnout suit, turnout boots, ballistic vest IV over the turnout suit)	20	1.54

Appendix D

Thermal insulation (male)

	Rt (Ensemble)	Rt (Torso)	Min	Max	Tmin	Tmax
E1	0.135333	0.159533	0.002733	0.002067	0.006033	0.004167
E2	0.146833	0.286	0.003833	0.002667	0.0034	0.0017
E3	0.3077	0.4455	0.0021	0.0034	0.0081	0.0068
E4	0.319278	0.571411	0.011578	0.004422	0.056311	0.006289
E5	0.3213	0.592567	0.0039	0.0024	0.018767	0.024733
E6	0.319533	0.569733	0.003433	0.002867	0.012333	0.008567

Evaporative resistance (male)

	Ret (Ensemble)	Ret (Torso)	Min	Max	Tmin	Tmax
E1	0.020246667	0.02484	0.000797	0.000733	0.00037	0.00044
E2	0.02269	0.07178	0.00027	0.00033	0.00028	0.0005
E3	0.05609	0.090503333	0.0009	0.0011	0.002773	0.003467
E4	0.065346667	0.173996667	0.000747	0.000653	0.040157	0.020933
E5	0.062656667	0.191506667	0.001927	0.002003	0.043617	0.036703
E6	0.060796667	0.227226667	0.001617	0.002953	0.023387	0.022633

Predicted total heat loss (male)

	Qp (Ensemble)	Qp (Torso)	Min	Max	Tmin	Tmax
E1	255.1667	210.5	4.466667	4.033333	0.9	1.3
E2	229.8667	86.9	0.966667	0.533333	1.1	1.6
E3	102.4667	66.23333	1.066667	0.733333	1.333333	1.266667
E4	88.12222	37.53333	1.522222	2.677778	0.233333	7.866667
E5	88.73333	36.86667	2.133333	2.066667	4.266667	4.933333
E6	88.06667	35.73333	1.366667	0.833333	1.233333	0.966667

Thermal resistance (female)

	R_t (Ensemble)	R_t (Torso)	Min	Max	Tmin	Tmax
E1	0.135133	0.179133	0.006233	0.004867	0.016133	0.012867

E2	0.145367	0.227267	0.005667	0.003033	0.020967	0.011433
E3	0.3237	0.544167	0.0031	0.0019	0.008567	0.004833
E4	0.312533	0.5369	0.016833	0.009467	0.0643	0.0424
E5	0.313267	0.533767	0.012767	0.008733	0.052467	0.039033
E6	0.313567	0.542367	0.008867	0.006033	0.032867	0.023633

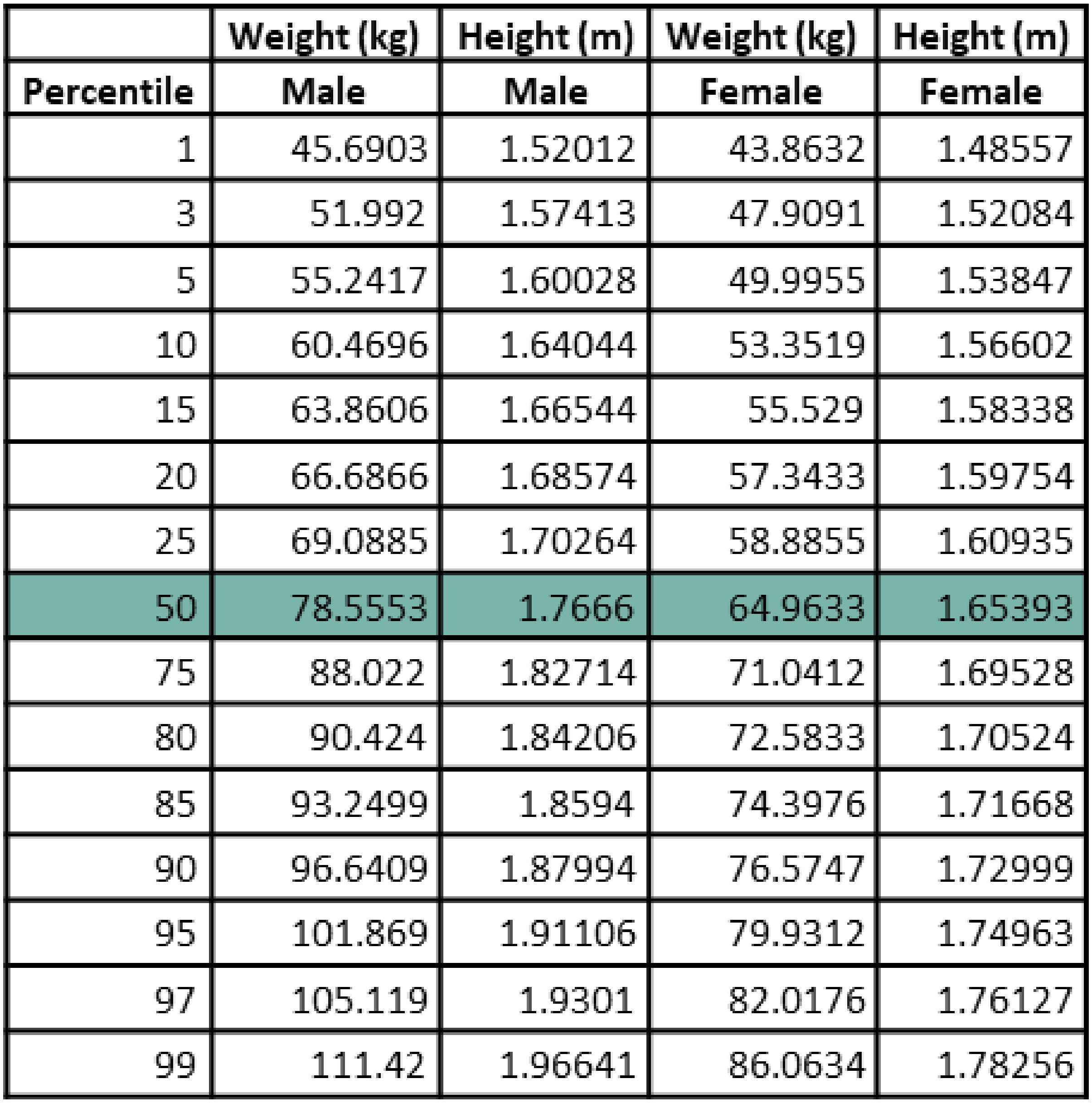
Evaporative resistance (female)

	R_{et} (Ensemble)	R_{et} (Torso)	Min	Max	Tmin	Tmax
E1	0.022017	0.028217	0.000507	0.000663	0.000557	0.000783
E2	0.023153	0.044833	4.33E-05	7.67E-05	5.33E-05	5.67E-05
E3	0.07101	0.144853	0.00304	0.00378	0.008843	0.010407
E4	0.065657	0.172181	0.004737	0.006733	0.0088	0.035969
E5	0.061723	0.157293	0.000803	0.000647	0.000323	0.000637
E6	0.064667	0.163833	0.000697	0.000453	0.003523	0.003567

Predicted total heat loss (female)

	Qp (Ensemble)	Qp (Torso)	Min	Max	Tmin	Tmax
E1	236.0333	182.2667	4.833333	3.766667	3.466667	2.533333
E2	222.8333	123.5667	0.533333	0.266667	0.066667	0.033333
E3	81.2	43.06667	2.6	2.2	1.766667	1.533333
E4	86.5	39.54444	5.1	4	3.744444	-1.14444
E5	89.73333	41.43333	0.633333	0.766667	0.133333	0.066667
E6	87.03333	40.2	0.333333	0.566667	0.5	0.5

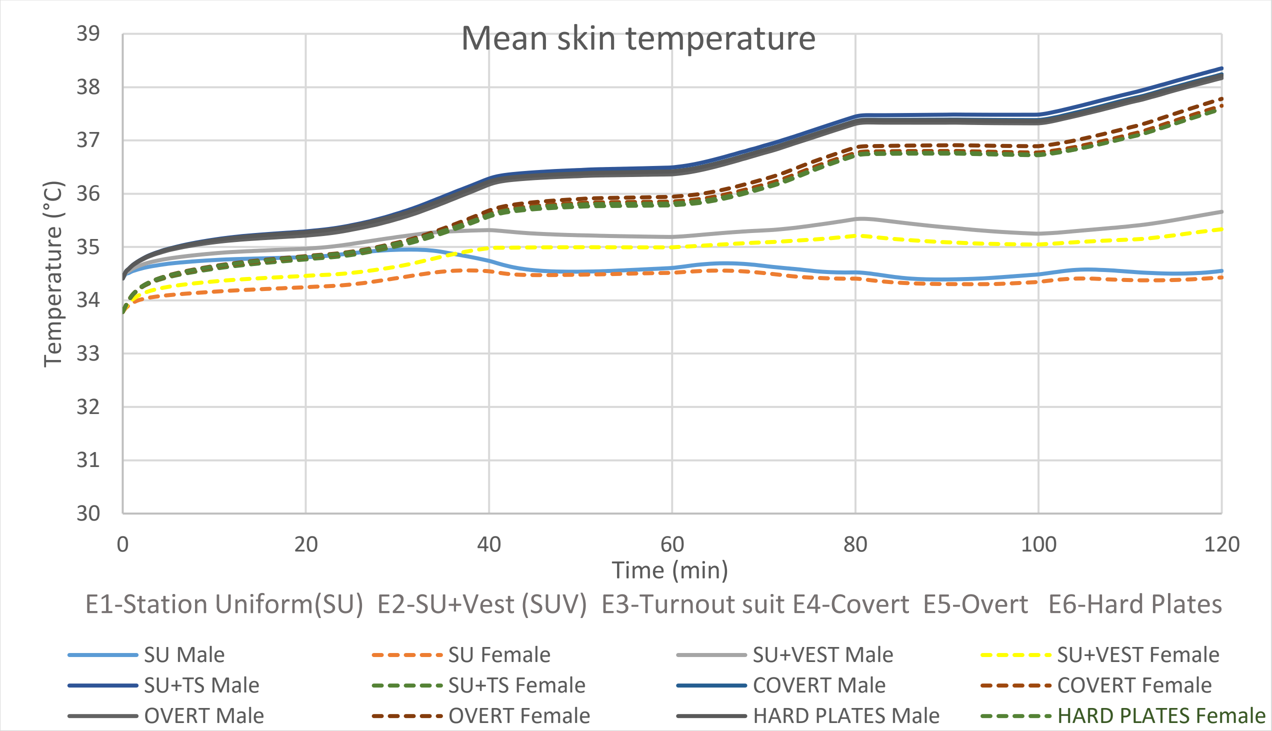
Appendix E

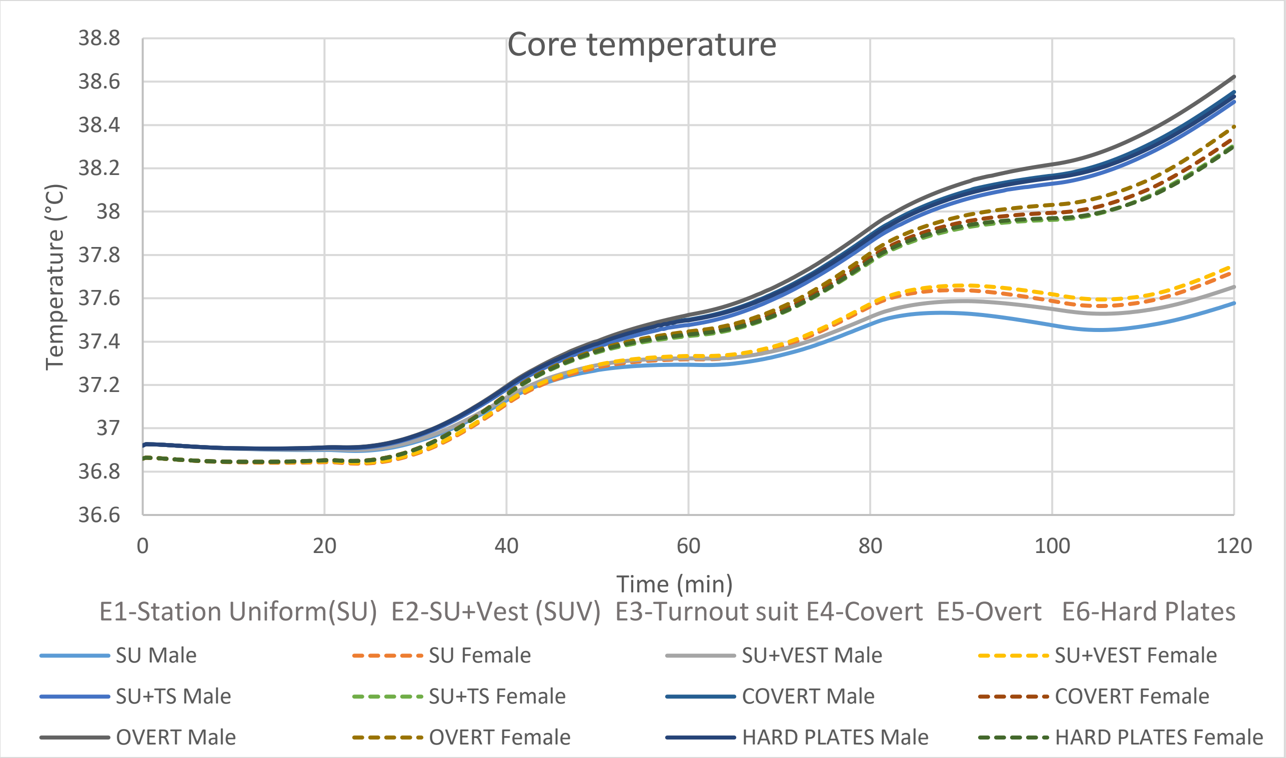


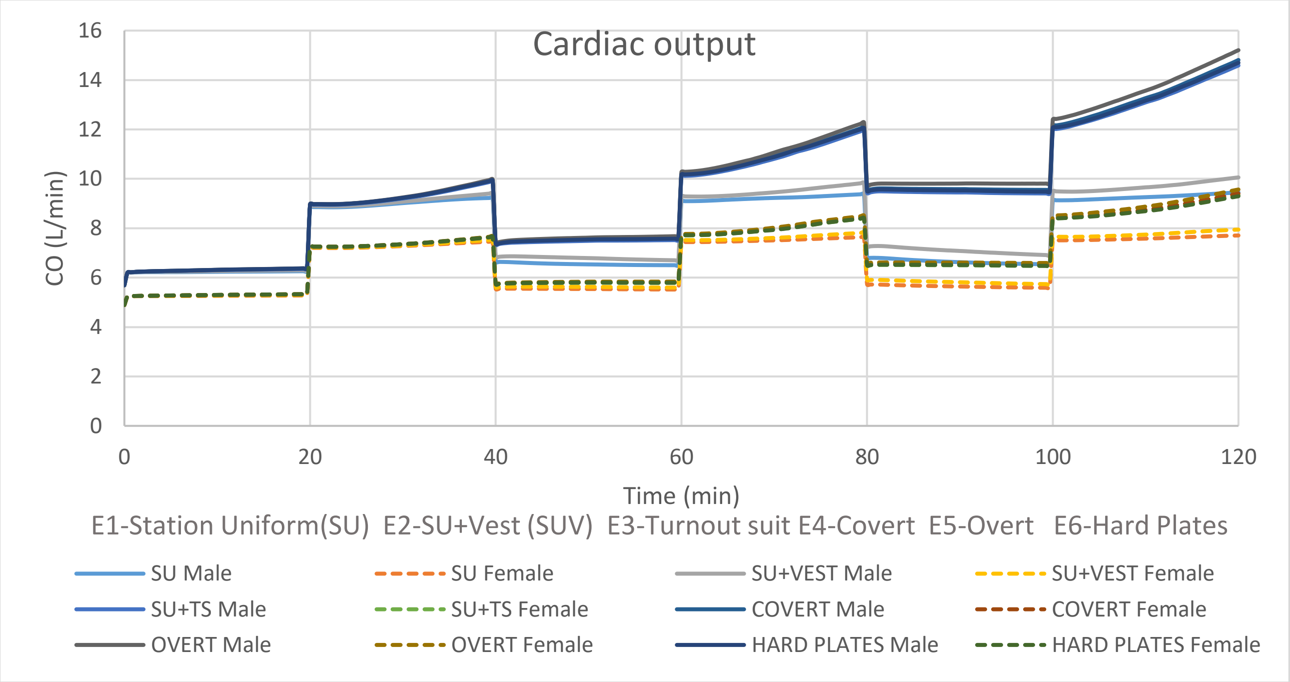
	Weight (kg)	Height (m)	Weight (kg)	Height (m)
Percentile	Male	Male	Female	Female
1	45.6903	1.52012	43.8632	1.48557
3	51.992	1.57413	47.9091	1.52084
5	55.2417	1.60028	49.9955	1.53847
10	60.4696	1.64044	53.3519	1.56602
15	63.8606	1.66544	55.529	1.58338
20	66.6866	1.68574	57.3433	1.59754
25	69.0885	1.70264	58.8855	1.60935
50	78.5553	1.7666	64.9633	1.65393
75	88.022	1.82714	71.0412	1.69528
80	90.424	1.84206	72.5833	1.70524
85	93.2499	1.8594	74.3976	1.71668
90	96.6409	1.87994	76.5747	1.72999
95	101.869	1.91106	79.9312	1.74963
97	105.119	1.9301	82.0176	1.76127
99	111.42	1.96641	86.0634	1.78256

Appendix F

Effect of gender:

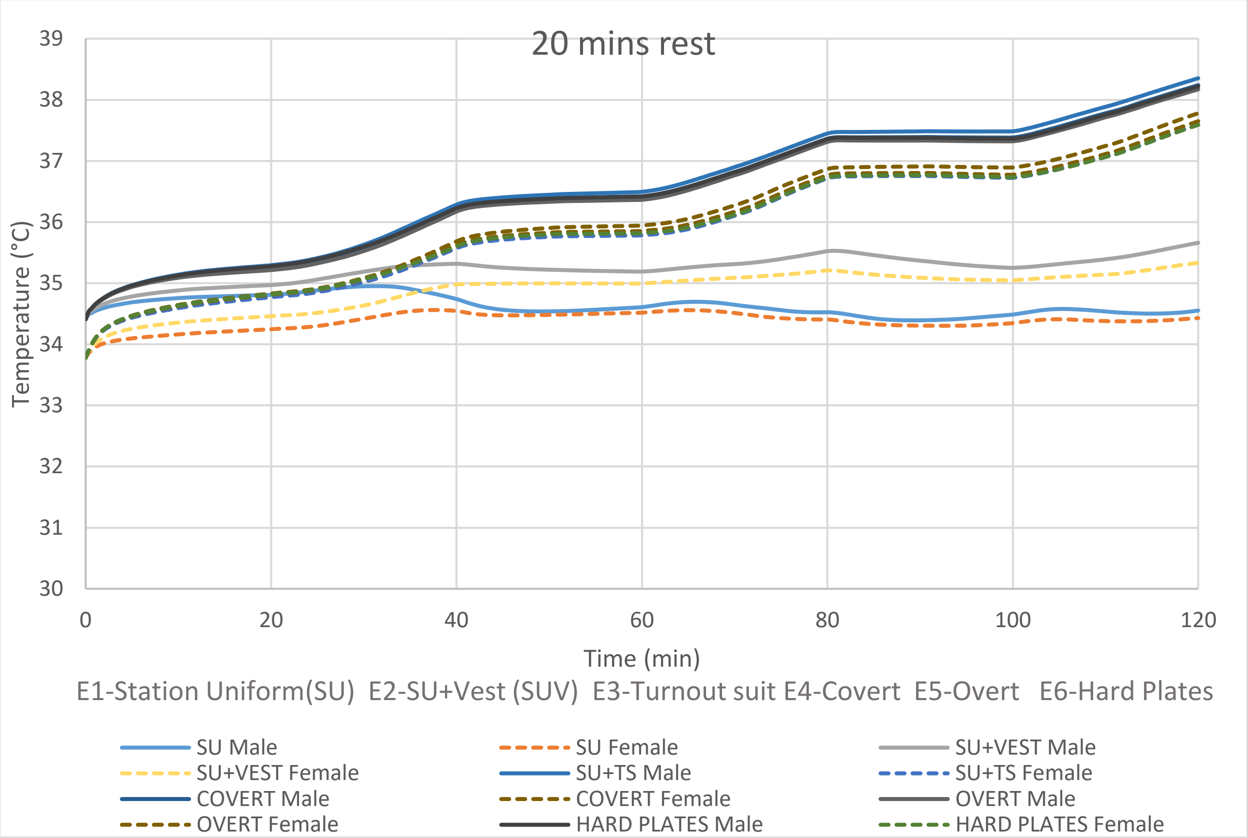


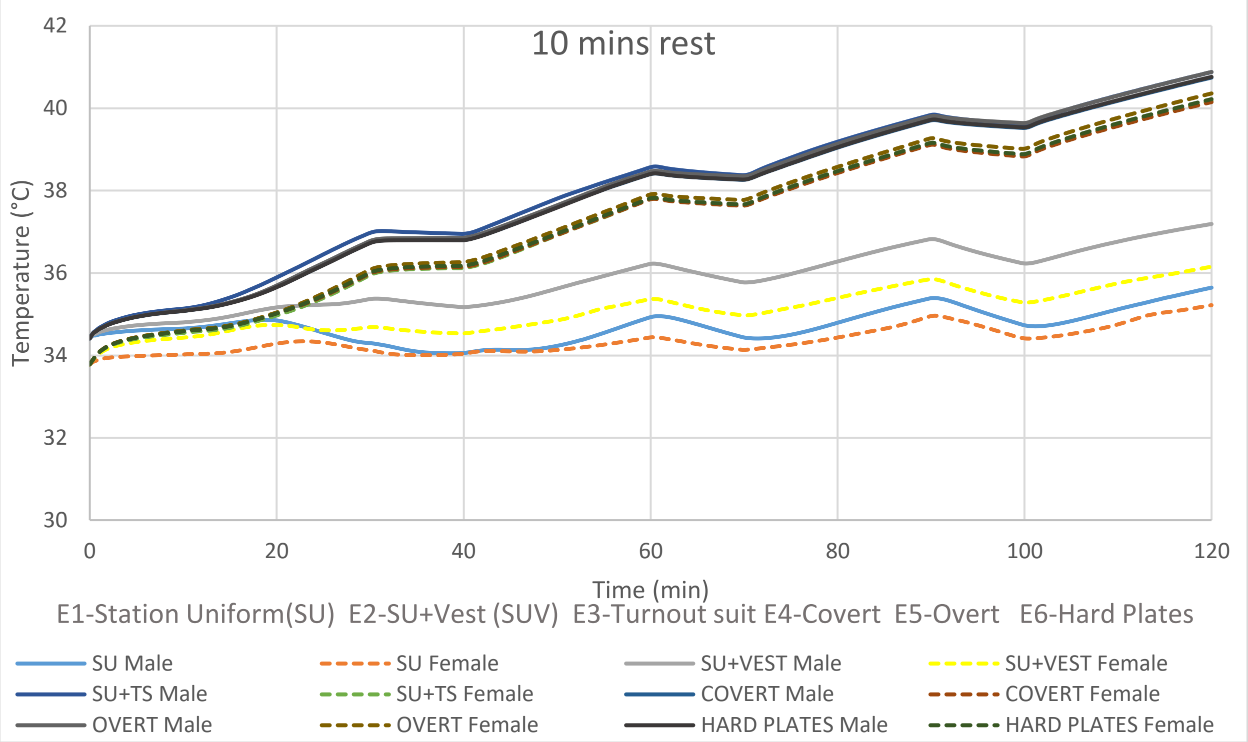

Core temperature
Temperature (°C)
38.8
38.6
38.4
38.2
38
37.8
37.6
37.4
37.2
37
36.8
36.6
0
20
40
60
80
100
120
Time (min)
E1-Station Uniform(SU) E2-SU+Vest (SUV) E3-Turnout suit E4-Covert E5-Overt E6-Hard Plates
SU Male
SU Female
SU+VEST Male
SU+VEST Female
SU+TS Male
SU+TS Female
COVERT Male
COVERT Female
OVERT Male
OVERT Female
HARD PLATES Male
HARD PLATES Female

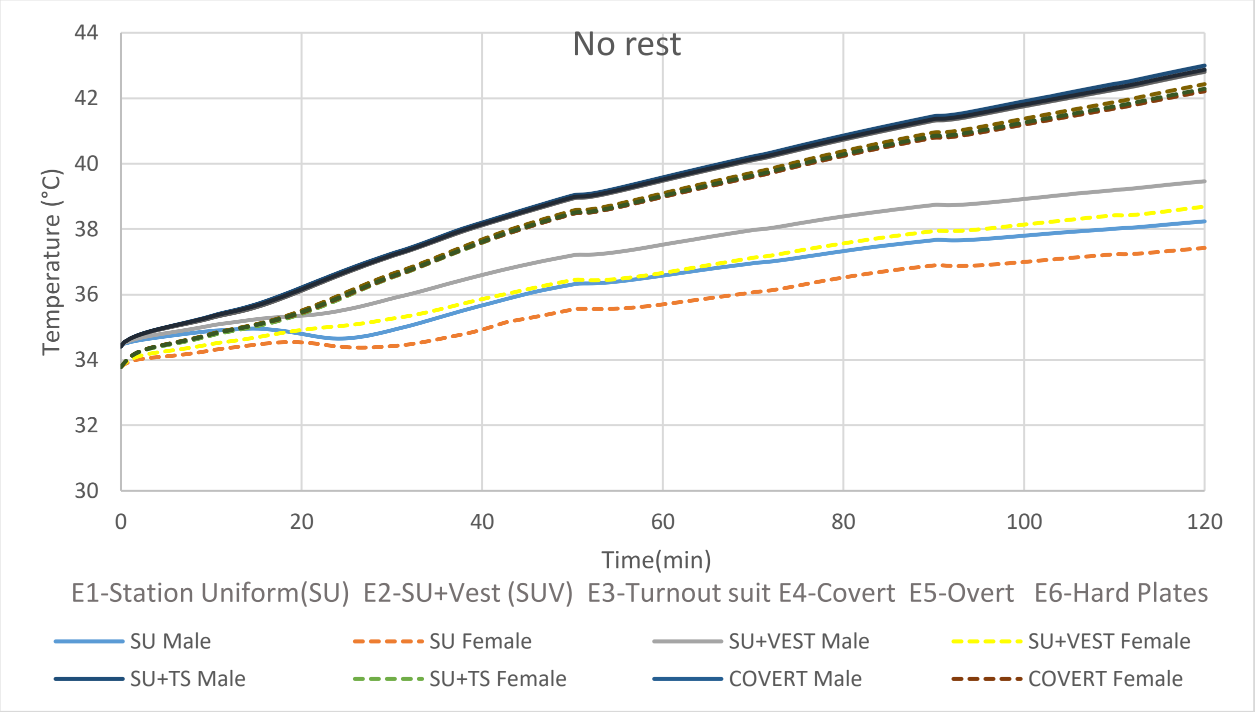

Cardiac output
CO (L/min)
16
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
Time (min)
E1-Station Uniform(SU) E2-SU+Vest (SUV) E3-Turnout suit E4-Covert E5-Overt E6-Hard Plates
SU Male
SU Female
SU+VEST Male
SU+VEST Female
SU+TS Male
SU+TS Female
COVERT Male
COVERT Female
OVERT Male
OVERT Female
HARD PLATES Male
HARD PLATES Female

Effect of rest time

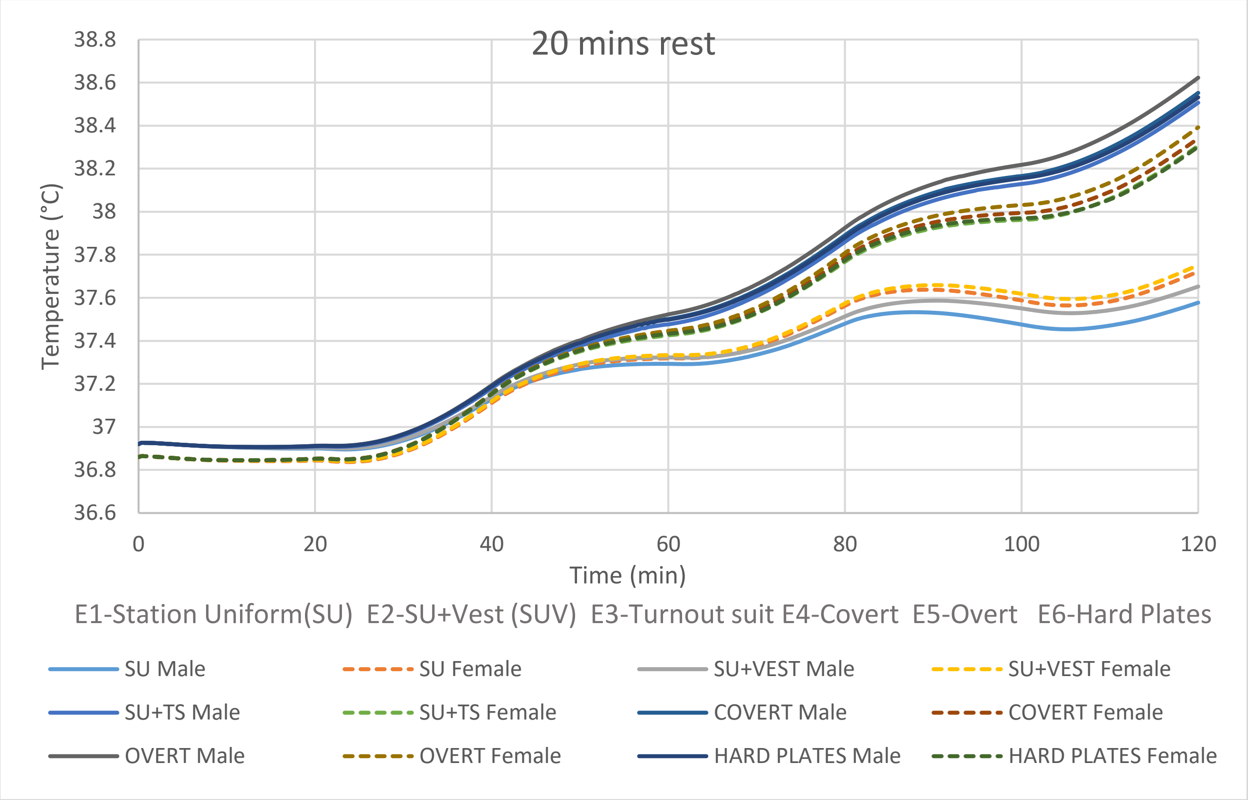
Skin temperature

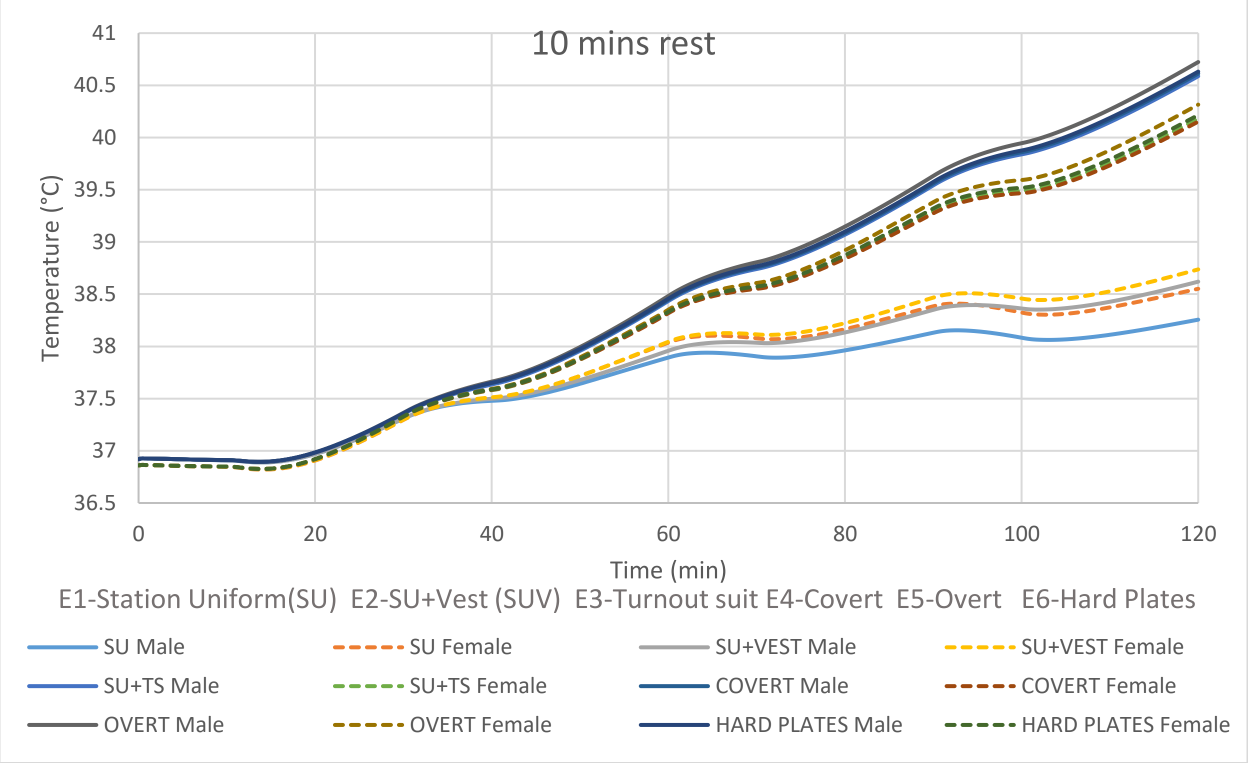


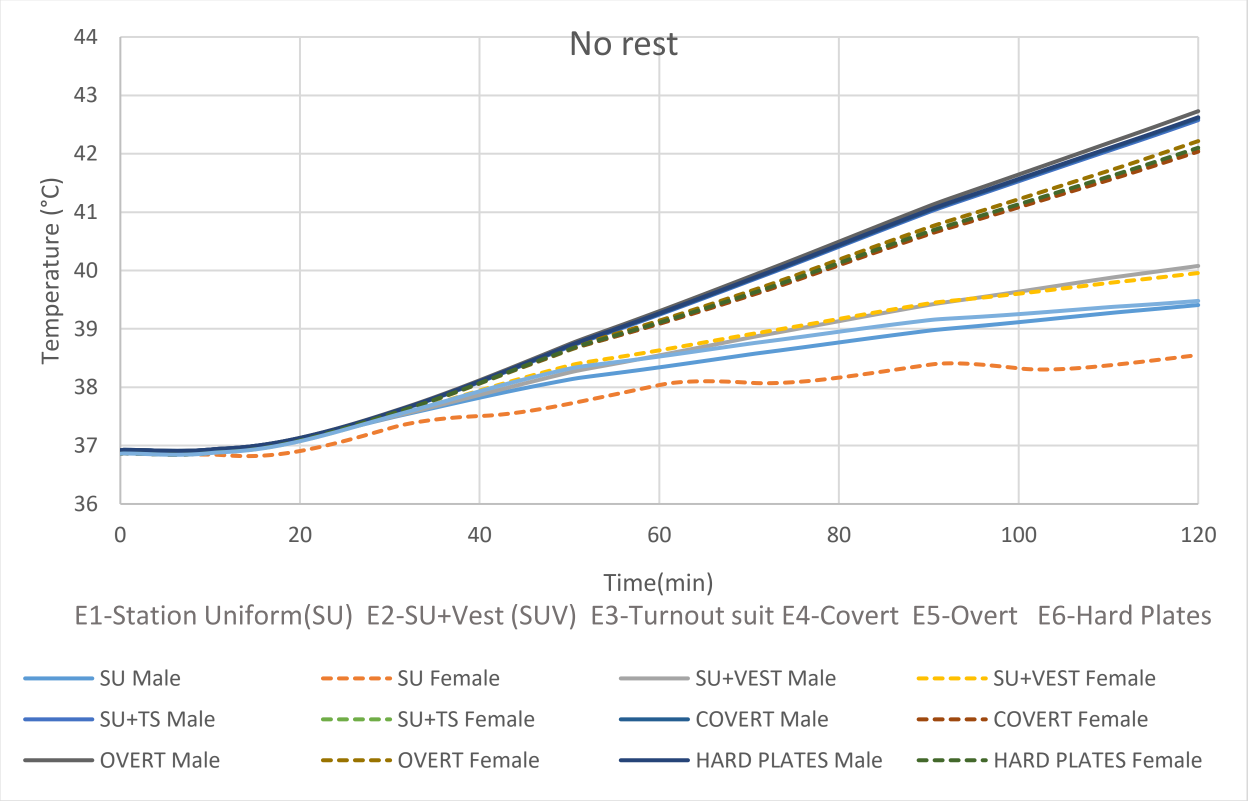

10 mins rest
Temperature (°C)
42
40
38
36
34
32
30
0
20
40
60
80
100
120
Time (min)
E1-Station Uniform(SU) E2-SU+Vest (SUV) E3-Turnout suit E4-Covert E5-Overt E6-Hard Plates
SU Male
SU Female
SU+VEST Male
SU+VEST Female
SU+TS Male
SU+TS Female
COVERT Male
COVERT Female
OVERT Male
OVERT Female
HARD PLATES Male
HARD PLATES Female


No rest
Temperature (°C)
44
42
40
38
36
34
32
30
0
20
40
60
80
100
120
Time(min)
E1-Station Uniform(SU) E2-SU+Vest (SUV) E3-Turnout suit E4-Covert E5-Overt E6-Hard Plates
SU Male
SU Female
SU+VEST Male
SU+VEST Female
SU+TS Male
SU+TS Female
COVERT Male
COVERT Female

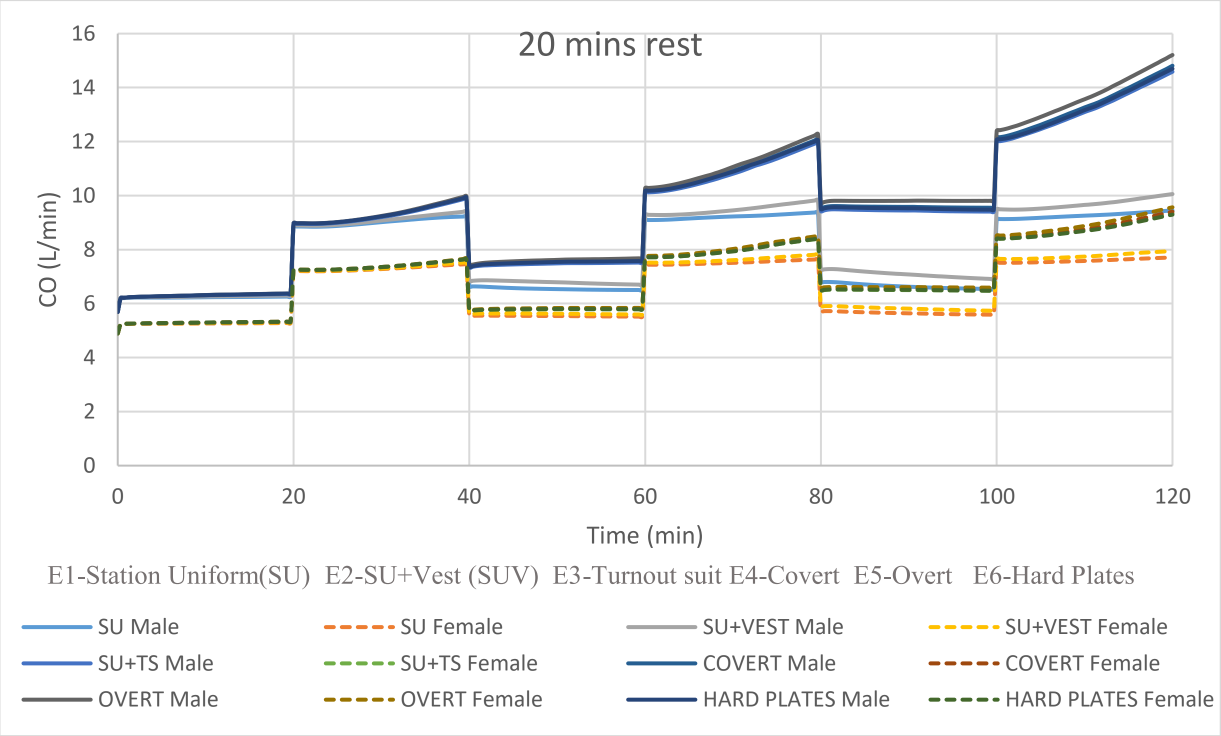
Core temperature

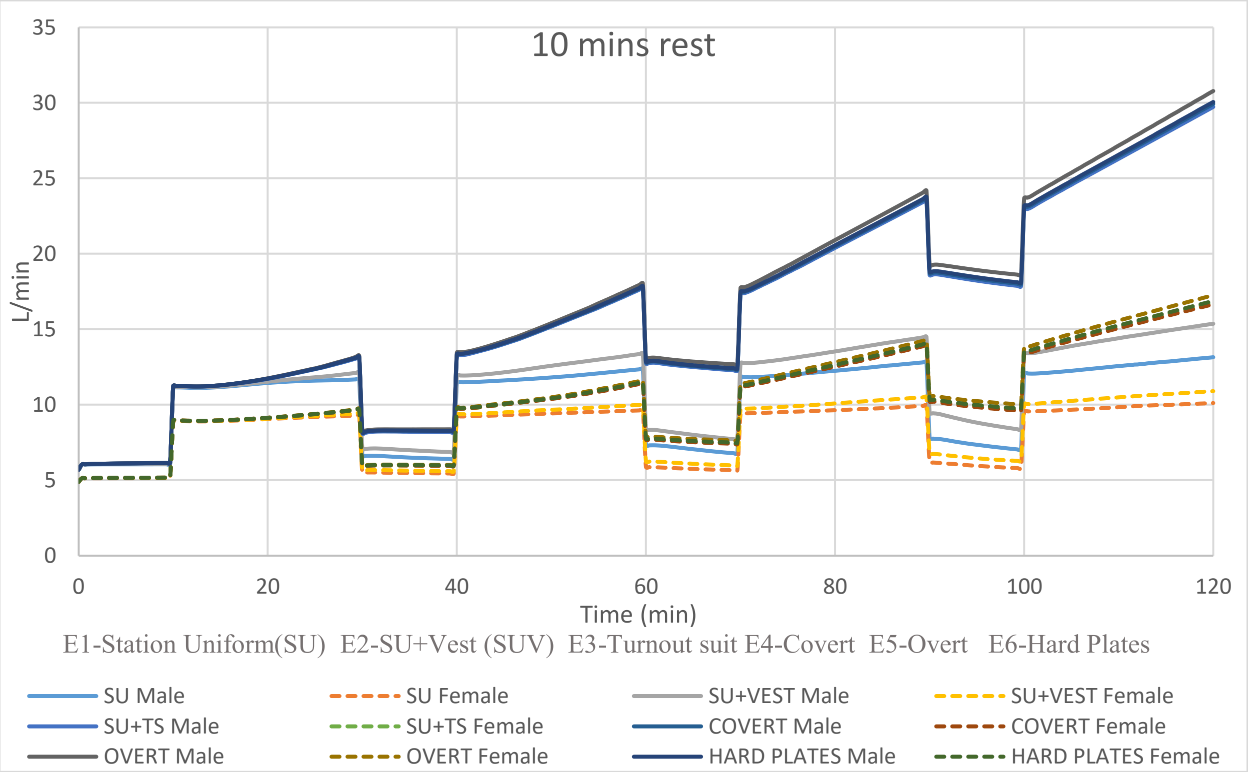


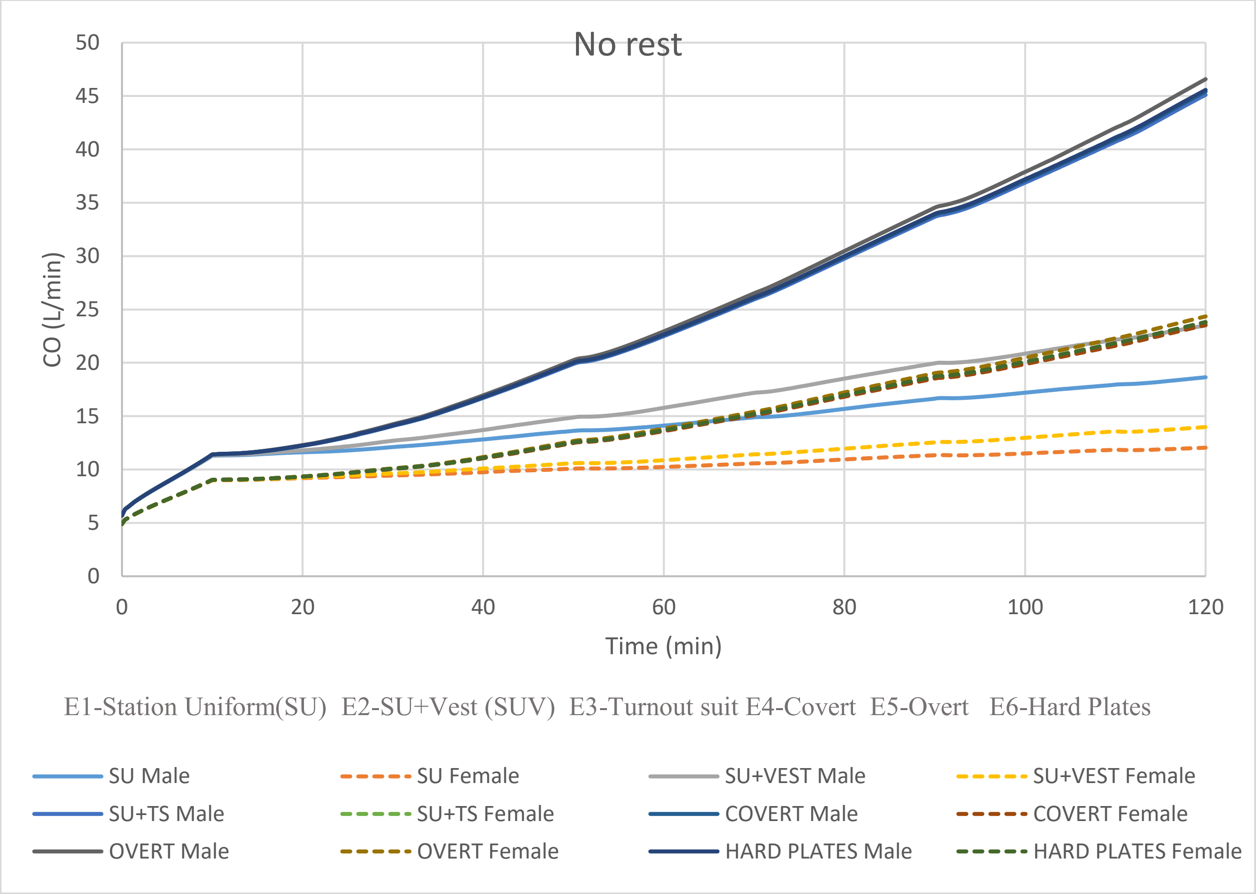

10 mins rest
Temperature (°C)
41
40.5
40
39.5
39
38.5
38
37.5
37
36.5
0
20
40
60
80
100
120
Time (min)
E1-Station Uniform(SU) E2-SU+Vest (SUV) E3-Turnout suit E4-Covert E5-Overt E6-Hard Plates
SU Male
SU Female
SU+VEST Male
SU+VEST Female
SU+TS Male
SU+TS Female
COVERT Male
COVERT Female
OVERT Male
OVERT Female
HARD PLATES Male
HARD PLATES Female


No rest
Temperature (°C)
44
43
42
41
40
39
38
37
36
0
20
40
60
80
100
120
Time(min)
E1-Station Uniform(SU) E2-SU+Vest (SUV) E3-Turnout suit E4-Covert E5-Overt E6-Hard Plates
SU Male
SU Female
SU+VEST Male
SU+VEST Female
SU+TS Male
SU+TS Female
COVERT Male
COVERT Female
OVERT Male
OVERT Female
HARD PLATES Male
HARD PLATES Female

Cardiac output






No rest
CO (L/min)
Time (min)
0
5
10
15
20
25
30
35
40
45
50
0
20
40
60
80
100
120
E1-Station Uniform(SU) E2-SU+Vest (SUV) E3-Turnout suit E4-Covert E5-Overt E6-Hard Plates
SU Male
SU Female
SU+VEST Male
SU+VEST Female
SU+TS Male
SU+TS Female
COVERT Male
COVERT Female
OVERT Male
OVERT Female
HARD PLATES Male
HARD PLATES Female