13th International Manikin & Modelling Meeting (I3M) and The Clothing and Textile Sciences Research Meeting (CTSRM) – Abstracts

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Extreme Heat Enabled Adaptive Thermal Manikin

Rick Burke (Thermetrics LLC)
Lyle Bartels (Thermetrics LLC)
Mark Hepokoski (ThermoAnalytics)
Konrad Rykaczewski (Arizona State University)

Abstract

Extreme heat exposure is a growing global health threat, exacerbated by climate change and rapid urbanization. Accurately modeling human thermo-physiological response under such conditions is critical for predicting heat-related illness and informing protective interventions. These models require precise environmental boundary conditions—inputs that are often difficult to measure accurately in real-world scenarios. Thermal manikins offer a unique advantage by capturing detailed human-environment heat exchange, enabling high-fidelity inputs for simulation models. Adaptive manikins couple these external measurements with internal physiological models to simulate real-time human response to heat stress. However, due to hardware and control limitations, existing manikins have only been able to achieve this coupling in heat loss scenarios, severely restricting their applicability in extreme heat environments.

This paper presents a novel coupling approach using ANDI, the dynamic heat-flux sensing manikin developed by Thermetrics LLC. In collaboration with ThermoAnalytics and Arizona State University, a new control architecture is implemented within the existing ManikinPC platform to enable temperature-controlled operation, in contrast to conventional heat flux-controlled approach. This shift allows the system to respond to simulated internal physiology in both heat gain and heat loss conditions.

The model is evaluated in a heat loss scenario by comparing it to a previous version of ManikinPC, which has already been validated for cold conditions, and in heat gain scenarios by comparing it to human trial data from widely referenced legacy studies. Initial results demonstrate strong agreement between simulated and measured physiological responses. This advancement enables accurate, real-time simulation of human thermoregulation in extreme heat, providing a powerful tool to help anticipate, mitigate, and ultimately reduce heat-related illness in an increasingly warming world.

Keywords: Extreme Heat, Adaptive Manikin, Thermal Physiology, Physiological Modeling

Quantifying Turbulent Convective Heat Transfer Using an Outdoor Thermal Manikin

Ankit Joshi (Arizona State University)
Shri H. Viswanathan (Arizona State University)
Cibin T. Jose (Arizona State University)
Gokul Pathikonda (Arizona State University)
Konrad Rykaczewski (Arizona State University)

Abstract

Accurately characterizing convective heat exchange between the human body and its environment is important for assessing thermal stress and comfort under a variety of conditions. Traditional convective heat transfer correlations, developed primarily from indoor studies, often fail to accurately represent complex outdoor environments characterized by transient airflow and turbulence. To address this gap, we employed a novel outdoor thermal manikin ("ANDI") equipped with 35-zone temperature and heat flux sensors, along with a three-level ultrasonic anemometer array and Integral Radiation Measurements (IRM), to quantify convective heat flux in diverse outdoor scenarios [1].

Field experiments were conducted over 20 days in shaded outdoor settings with air temperatures up to 45°C, wind speeds ranging from 0.7 to 4.5 $m \cdot s^{-1}$, turbulence intensities as high as 46%, and turbulence length scales between 0.5 and 15 m. Results indicated a robust correlation between local convective heat transfer coefficients and wind speeds, emphasizing that turbulence intensity and length scale significantly influence convective heat transfer. By fitting our measured data to the established Kondjoyan-Daudin-Sak correlation for turbulent cross-flow, we determined universal, geometry-based parameters, resolving existing discrepancies among traditional correlations.

The outcome is a geometry-informed correlation that accurately predicts convective heat transfer across diverse body segments, sizes, and environmental conditions, suitable for both indoor and outdoor settings. The improved predictive accuracy can inform urban design, outdoor activity guidelines, and protective clothing strategies, enhancing human adaptation to increasingly severe heat exposure.

[1] Joshi et al., Sci. Total Env., 2024.

Keywords: convection, turbulence, outdoor thermal manikin

ANDI DeVil: Two-color Outdoor Manikin for Quantifying Complex Shortwave and Longwave Irradiation Across the Body and Apparel Radiation Attenuation Performance

Kambiz Sadeghi (Arizona State University)
Lyle Bartels (Arizona State University)
Ankit Joshi (Arizona State University)
Shri Viswanathan (Arizona State University)
Cibin Jose (Arizona State University)
Ariane Middel (Arizona State university)
Konrad Rykaczewski (Arizona State University)

Abstract

Outdoor environments can be shaped to improve human thermal comfort, but research often evaluates comfort at the whole-body level, overlooking the inherently uneven way the body exchanges heat with its surroundings. For example, radiation effects are typically reduced to a single parameter, the mean radiant temperature, neglecting the distinct roles of shortwave and longwave radiation. Shortwave radiation, in particular, tends to strike the body unevenly, leading to localized discomfort, yet no existing tools adequately capture these detailed irradiation patterns. To fill this gap, we developed two complementary methods. The first uses a "two-color" outdoor thermal manikin ANDI, whose surface temperature is set equal to that of air to eliminate convection. About half of the manikin is painted white, which allows to isolate the spectral irradiation components by comparing fluxes measured across symmetrical zones of varying colors [1]. The second approach converts field-measured 6-directional radiometer fluxes into boundary conditions for ANDI's virtual twin simulations. We applied both methods during outdoor field studies across sunlit, partially shaded, and fully shaded settings in warm to extreme heat conditions. Overall, the two techniques produced consistent results, with differences revealing specific advantages of each. We also assessed how five long-sleeve shirts of varying color, from white to black, attenuated incident radiation. Wearing of the shirts reduced the rate absorbed heat by the bare upper body (i.e., tan shell) from 159W to 73.3W (white fabric), 86.7W (light blue fabric), 128W (dark blue fabric), 117W (maroon fabric), and 127W (black fabric). These methods offer a path toward integrating radiation data into airflow and thermoregulation models, enabling more refined and human-centered outdoor built environment design as well as approach to quantify radiative performance of apparel in realistic outdoor conditions.

[1] Sadeghi et al., Building and Environment, 2025.

Keywords: outdoor thermal manikin, spectral irradiation, radiative textile testing

Quantifying Free Convective Heat Transfer in Cold and Hot Indoor Conditions Using Complementary Thermal Manikin Experiments and Multiphysics Modeling

Shri Viswanathan (Arizona State University)
Ankit Joshi (Arizona State University)
Konrad Rykaczewski (Arizona State University)

Abstract

Accurately characterizing free convective heat exchange between the human body and indoor surroundings is critical for ensuring thermal comfort, health, and productivity. However, existing correlations for the free convection heat transfer coefficient (hfree) show wide disagreement, undermining their reliability. Furthermore, all such correlations were developed for cooler indoor conditions, leaving free convection in hotter environments—typical of indoor overheating—largely unexplored. To address these gaps, a 3D computational multiphysics model coupling fluid flow and heat transfer was developed and validated against experiments conducted with a 35-zone thermal manikin ("ANDI") inside a sealed enclosure with air temperatures spanning from 20.1 to 44.2 °C. The measured and simulated whole-body heat fluxes differed by no more than 5.2%, demonstrating strong agreement. Using this validated model, a parametric investigation of commonly cited methodological discrepancies in the literature—such as manikin gender and skin temperature control mode—revealed minimal impact on hfree (<1.1%). Instead, the primary cause of the disagreement was traced to inaccurate separation of convective and radiative heat fluxes, driven by procedural errors and oversimplified view factor assumptions. This work confirms the accuracy of, and promotes the use of, computational delamination techniques to resolve individual heat transfer pathways, namely convection, radiation, and evaporation. The model also yields accurate whole-body and regional hfree correlations. While whole-body values remain consistent across cool and warm conditions, regional values vary with the direction of buoyant plume flow and body part height. These validated correlations improve indoor heat stress assessment and enhances the design of effective extreme heat mitigation strategies.

Keywords: thermal manikin, free convection, multiphysics modeling

Evaluation of Heat Stress Prediction for Structural Internal Firefighting Scenario

Amber M. H. Klomp (Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam)
Lotte M. G. Jacobs (Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam)
Hein A. M. Daanen (Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam)
Kalev Kuklane (Estonian University of Life Sciences & Netherlands Institute for Public Safety (NIPV), The Netherlands)

Abstract

Firefighters face hazardous conditions that can induce negative physiological and psychological responses, more specifically heat strain. The Predicted Heat Strain model (PHS, ISO7933) enables the determination of heat strain while considering clothing properties, environment and activity in predictive calculations. However, PHS was originally developed for industrial applications. For suggesting potential adjustments in ISO 7933 for firefighter work, this study aimed to evaluate PHS algorithms for firefighters under simulated structural interior firefighting activities (SIF).

Four firefighters wearing turnout gear performed pre-work and recovery at room temperature, and intermittent activities in a climate-controlled room (Ta = 44.4 ± 0.2 °C, RH = 27.8 ± 1.6 %, va < 0.15 m/s). Clothing thermal insulation and evaporative resistance were determined using a thermal manikin. Skin (Tsk) and rectal temperatures (Trec), and body water loss (mwl) were compared with PHS predictions using two online tools that allow input of intermittent conditions – FAME Lab (PHSFL) and the Lund University modified PHS (PHSLU).

Experimental Trec did not differ significantly from the PHSLU predictions. For PHSFL, Trec became significantly lower at the end of heat exposure and during recovery. Experimental Tsk was initially lower than predicted by PHSFL. Predicted Tsk decreased more rapidly than measured values at the end of radiation period for PHSLU, while reduction in PHSFL occurred slightly later. Both models predicted Tsk values that were lower than the experimental data throughout the recovery period. Overall the PHS models gave reasonably accurate predictions for both Trec and Tsk in this scenario (RMSD < SD), but mwl (> 1000 g) exceeded significantly measured one (630 ± 209 g).

The models may not adequately account for thermal inertia of the clothing system and/or heat distribution within it. Considering other scenarios and existing literature, it is clear that the PHS model requires adjustments for realistic predictions under firefighter conditions. Further detailed analysis is needed to determine the necessary modifications.

Keywords: firefighter, protective clothing, predicted heat strain, heat stress, physiological responses

Human Thermal Modeling of Patients under General Anesthesia

Mark Hepokoski (ThermoAnalytics)
Alexia Canull (ThermoAnalytics)
Carlos Guerra-Londono (Department of Anesthesiology, Pain Management, & Perioperative Medicine, Henry Ford Hospital).

Abstract

Anesthesia modifies thermoregulatory function by adjusting the temperature threshold, gain and maximum intensity of shivering, vasomotion and sweating [1] [2]. Anesthesia also reduces metabolism [3]. General anesthesia exhibits a characteristic pattern, described by three consecutive stages of core temperature progression: 1) a rapid drop; 2) then a slower, nearly linear decrease; and finally, 3) stabilization to a plateau [4].

References

[1] Kurz et al., 2008, DOI: 10.1016/j.bpa.2007.10.004

[2] Kim et al., 1998, DOI: 10.1097/00000542-199804000-00002

[3] Briesenick et al., 2023, DOI: 10.1213/ANE.0000000000006343

[4] Sessler, 2000, DOI: 10.1097/00000542-200002000-00042

Keywords: human thermal model, thermoregulation, physiology, anesthesia, simulation

Sweat Evaporation Dynamics: In Vivo vs On Manikin Observations

Cibin T. Jose (Arizona State University)
Ankit Joshi (Arizona State University)
Shri H. Viswanathan (Arizona State University)
Sincere K. Nash (Arizona State University)
Stavros Kavouras (Arizona State University)
Konrad Rykaczewski (Arizona State University)

Abstract

Effective evaporation of sweat is the main way human bodies cool off in hot environments, while impeded evaporation leads to sweat accumulation and thermal discomfort. Therefore, it is important to understand the fundamentals of the sweat evaporation process and how environmental conditions, physiological characteristics, and textile design alter it. The most common assumption in thermoregulation models and textile testing is that sweat is an isothermal film at the temperature of the underlying skin. In textile testing, this assumed physiological feature is mimicked using thin fabric “skin” that wicks water dispensed from “sweat pores” over the shell of thermal manikins. In this presentation, we will first discuss our multi-method in vivo microscale observations and measurements of sweat evaporation dynamics. In particular, we will discuss coupled microscale mid-wave infrared, visible range, and optical coherence tomography imaging of pore-level sweating dynamics and evaporation rate measurements performed using a mini-wind tunnel ventilated capsules with varied humidity and flow rates [1]. We will also discuss these “microscale” measurements in the context of additional “macroscale” measurements, including cylindrical ventilated capsule sweat rate, galvanic skin conductance, and capacitive stratum corneum hydration measurements. We will discuss the cyclic dropwise, transition, filmwise, and “puddle-wise” skin sweating modes, their relation to evaporation rate and environmental conditions, and settings in which the isothermal film assumption is adequate. We will conclude by discussing ANDI’s sweating skin performance, which was determined via “dry” and “wet” convection experiments, and its comparison against the in vivo observations.

[1] Jaiswal et al., iScience, 2024.

Keywords: sweat evaporation, microscale imaging, sweating fabric skin

Predicting Human Thermal Responses During Exercise in Heat and Cold Using Finite Element Thermoregulatory Models

Stefan Gutierrez (United States Army Research Institute of Environmental Medicine)
Juliette Jacques (United States Army Research Institute of Environmental Medicine)
Timothy Rioux (United States Army Research Institute of Environmental Medicine)
Gabrielle Gierch (United States Army Research Institute of Environmental Medicine)
Afton Seeley (United States Army Research Institute of Environmental Medicine)
John Castellani (United States Army Research Institute of Environmental Medicine)
Xiaojiang Xu (United States Army Research Institute of Environmental Medicine).

Abstract

Introduction. Recently, two geometry-specific finite element thermoregulatory models (FETM) with medical image-based geometry were successfully developed (Castellani et al., 2021; Castellani et al., 2023) and validated primarily in resting conditions. This investigation aims to further validate FETM predictions against physiological data collected during exercise in hot and cold conditions.

Methods. The FETMs were developed in a finite element software (COMSOL Multiphysics). Model predictions were validated with physiological data collected during exercise in hot and cold conditions. Dataset 1: Twenty-nine volunteers walked on a treadmill at an average 359W (estimated by Pandolf equation) for 120 minutes in a 40ºC, 40% relative humidity environment wearing military PT clothing. Core (Tcore) and four skin temperatures (Tsk) were collected. Dataset 2: Twelve adults wearing different military ensembles completed three trials in 5°C air. Volunteers rested for 60 min followed by two 60 min walks at an average 347W and 382W. Tcore and eleven site Tsk were collected (Seeley et al., 2024). Differences between observed values in Tcore and Tsk were evaluated by comparing root mean square deviations (RMSD) with observed standard deviations (SD). If RMSD was less than SD, predictions were considered valid.

Results. In 40°C conditions, predicted Tcore was within observed values towards the end of experiment and the predicted chest Tsk were within the mean ± SD. RMSD were 0.37°C and 0.19°C for core and chest temperatures, respectively. Observed SD for core and chest temperature were 0.40°C and 0.66°C, respectively.

In 5°C wet clothing conditions, predicted Tcore were below the observed values by an average 0.76°C. Predicted Tsk were within the mean ± SD. RMSD was 0.84 °C and 1.27°C for Tcore and Tsk, respectively. Observed SD for core and skin temperature were 0.4°C and 1.25°C, respectively.

Discussion/Conclusion. Predicting high resolution temperature distributions enable better understanding on how to improve human thermoregulation. Our validation demonstrates that the models predict spatial temperature with acceptable accuracy in hot exercising conditions. In cold conditions with wet clothing, the FETM predicted skin temperature with acceptable accuracy; however, core temperature was underpredicted. Further investigation needs to be conducted to understand why.

Keywords: Thermoregulation, Hot, Cold, Modelling, FETM, Wet Clothing, Exercise

Biophysical Evaluation of Heated Casualty Hypothermia Bags

Madeline Poley-Bogan (United States Army Research Institute of Environmental Medicine)
Timothy P. Rioux (United States Army Research Institute of Environmental Medicine)
John W. Castellani (United States Army Research Institute of Environmental Medicine)
Xiaojiang Xu (United States Army Research Institute of Environmental Medicine)

Abstract

Heated casualty hypothermia bags are specialized medical bags that transport injured victims to medical treatment facilities. Hypothermia and cold injury are significant factors during transportation, especially in cold or extreme environments and following trauma. Maintaining body temperature during transport is critical, and battery-powered heated hypothermia bags could be a potential approach to maintain human safety and prevent cold injury during exposure to cold environments. Thus, the objective of this study was to evaluate the thermal resistance (clo) and heating performance (W) of heated casualty hypothermia bags at three power settings – low, medium, and high – using a whole-body, dynamic sweating thermal manikin. Four bag configurations were tested in a controlled environmental chamber, with environmental conditions set to an air temperature of 6°C, 55% relative humidity (RH%), and air velocity of 0.3 m·s-1. The heated bags were evaluated using a nude manikin positioned horizontally on a cot, with measurements collected according to ASTM F1720-17. The manikin's Dynamic Heat Flux Sensors (DHS) and internal cooling system were utilized, allowing for negative (gaining heat from the environment) heat flux measurements with the addition of an external heating system. The average heating power for Bag A, Bag B, Bag A with Outer Insulation, and Bag B with Outer Insulation were 14.9W, 6.1W, 11.9W, and 5.6W, respectively. Results showed an increase in thermal insulation as the heating power levels increased. Additionally, results also demonstrated a decrease in heating power (W) as outer insulation was added, indicating that it requires less power to maintain the same temperature. Backside cooling system appears to reduce variations of measured parameters, however, its impact on measured results and benefits require further research.

Keywords: Thermal Manikin, Thermal Resistance, Cold Injury, Hypothermia Bags, Clothing Biophysics, Insulation, Heating System

Predicting the Effectiveness of Structural Internal Firefighting Gear using Computational Thermal Modeling.

Savannah Page (ThermoAnalytics, Inc.)
Mark Hepokoski (ThermoAnalytics, Inc.)
Timofey Golubev (ThermoAnalytics, Inc.)
Kalev Kuklane (Netherlands Institute for Public Safety (NIPV)

Firefighters are commonly exposed to high radiant temperatures while performing intense physical activity, which can result in significant thermal strain as indicated by elevated body temperatures. It is therefore essential that firefighters wear breathable, but sufficiently protective clothing to keep them safe, without which could lead to severe burns, dehydration, and heat stroke. Previous research has shown that computational modeling can be employed to determine the effectiveness of technical rescue gear. In this study, a computational thermal model was used to reproduce human subject tests comparing two types of firefighter turnout gear in a structural internal firefighting (SIF) scenario.

Human subject testing incorporated nine Dutch firefighters. Four participants wore a traditional set of firefighter turnout gear, SIF-T, and five wore a new system with a double layer jacket, SIF-D. An IR radiation panel was positioned to the right of the test person, to achieve 4 kW/m2 radiation at the right upper arm. The SIF scenario was defined by seven consecutive stages with varied walking intensity on a treadmill and intermittent periods of IR radiation. Rectal temperature, mean skin temperature, heart rate, and oxygen consumption rate (VO2) were recorded.

A human model in the TAITherm™ thermal modeling software was set up to reproduce the SIF test scenarios. The model considers all modes of heat transfer, including latent heat transfer, and contains a sophisticated human thermophysiology model that simulates passive and active thermoregulation. Convection around the human was estimated using the treadmill speed. Measured local clothing properties were applied to the segments of the human body and subdivided into nine discrete layers to capture internal temperature transients over the course of the simulated exposures.

Despite the traditional clothing set SIF-T having a slightly steeper rise in mean skin and rectal temperatures as compared to the SIF-D ensemble, the measured differences between the two ensembles were minor. Model predictions for both ensembles showed good agreement with test data, reproducing the trends and consistently remaining within one standard deviation of skin and core temperature measurements. This study demonstrates the value of using computational modeling for evaluating the effectiveness of structural internal firefighting gear.

Keywords: firefighter, protective clothing, computational thermal modeling, thermal insulation

The Influence of Friction and Pressure Exerted by Weft-Knitted Fabrics on Motion Control

Hoorieeh Abbasi Mahmoodabadi (Department of Textile Engineering (FPS) NCSU)
Emiel Denhartog (Department of Textile Engineering (FPS) NCSU)
Minyoung Suh (Department of Textile and Apparel Technology and Management, NCSU)

Abstract

Clothing is an indispensable component of daily life, influencing comfort, functionality, and overall health. Consequently, optimizing garment design by examining the influence of knitted fabric structures on applied friction and pressure distribution is essential for enhancing well-being and performance. A comprehensive understanding of the mechanical behavior of these fabrics allows for the refinement of their design, facilitating improved applications in rehabilitation, sportswear, and other performance-driven domains.

Current research particularly focuses on the areas prone to be under friction and stress during movement. This study employs an experimental approach, developing prototypes of compression arm sleeves with various knitted structures. Key to the experimental setup is the use of a localized friction measurement device, and pressure sensors to analyze fabric-skin interactions. Essential parameters, including friction force and applied pressure, were meticulously measured to evaluate their influence on motion control. Motion control was assessed using a motion capture system and quantified by analyzing the distance between the wrist marker and a designated reference marker. The findings demonstrated that the 1×1 mock rib and 1×1 mock rib with inlay notably enhanced the frictional and pressure properties exerted on the skin, thereby improving motion control. This suggests that elevated frictional forces and applied pressures result in a reduced distance between the wrist and the reference marker, which can be strategically leveraged to optimize stability and refine motion control.

These findings lay the foundation for future advancements in functional clothing design, bridging the gap between textile engineering and human biomechanics. They offer critical insights that drive the innovation of next-generation compression garments, optimizing performance.

Keywords: Friction, Pressure, Weft, Knitted, Motion, Control

Effects of Wet Clothing on Human Thermoregulation: Manikin Testing and Simulation

Xiaojiang Xu (US Army Research Institute of Environmental Medicine)
Timothy P. Rioux (US Army Research Institute of Environmental Medicine)
Stefan A Gutierrez (US Army Research Institute of Environmental Medicine)
Madeline Poley-Bogan (US Army Research Institute of Environmental Medicine)
Afton D. Seeley (US Army Research Institute of Environmental Medicine)
John W Castellani (US Army Research Institute of Environmental Medicine)

Abstract

The project examined the effects of wet clothing on insulation and human thermal responses in cold air. Three military ensembles were tested on a thermal manikin using a newly established protocol for wet clothing. The order of testing for the new protocol included: a) saturate and spin clothing to remove excess water; b) seal saturated clothing in bag; c) condition clothing for at least 8 hours; d) dress the wet clothing on a thermally steady state manikin and e) measure thermal resistance continuously until the manikin reaches a new steady state. Human thermal responses while wearing wet clothing were simulated by the Six Cylinder Thermoregulatory Model (SCTM). Predicted core and skin temperatures were compared with physiological data to determine appropriate wet values for SCTM simulation. Dry thermal resistances of the ensembles were 1.26 to 1.35 clo. Their wet thermal resistances were dynamic, beginning at 0.8 clo (60% of dry values), and increasing over the 6 to 8 hour drying period. Predicted core and skin temperatures with different wet insulations (20, 60, 80 and 100% of dry values) were compared to the values observed during rest and exercise in 5°C air while wearing very wet ensembles (wet due to clothed head-out immersion). The comparison showed that using 20% of dry values was appropriate for simulating very wet ensembles. Thus, wet insulation could be as low as 20% for very wet (water dripping) to 60% or higher (no dripping). This simulation indicates that the extent of clothing saturation is a critical factor in understanding cold injury risk and safe cold air exposure duration.

Disclaimer: Author views not official US-Army/DOD policy

Keywords: wet clothing, cold stress, thermoregulatory model, modeling

Possibilities of Measurement with a Thermal Sweating Manikin

Bianca-Michaela Wölfling (Hohenstein Innovations gGmbH)
Edith Classen (Hohenstein Innovations gGmbH)

Abstract

Thermal sweating manikins offer a unique and precise method for evaluating the thermal and evaporative properties of clothing systems. This paper explores the possibilities of measurement using these advanced manikins, focusing on their ability to simulate human sweating and movement. The study aims to provide insights into the effectiveness of different garment designs in managing heat and moisture, thereby enhancing wearer comfort and performance. Methods include controlled experiments in climate chambers, utilizing DIN EN ISO 15831, ASTM F1291, DIN EN 17528, and ASTM F2370 standards. Results indicate significant variations in thermal insulation and evaporative resistance across different clothing ensembles. The discussion highlights the advantages of using thermal sweating manikins over traditional human trials, emphasizing their precision, repeatability, and ability to test under extreme conditions.

Furthermore, the study delves into the implications of these findings for the textile industry, particularly in the development of high-performance sportswear and protective clothing. By simulating real-world conditions, thermal sweating manikins provide a comprehensive understanding of how garments behave under various environmental stresses. This allows designers to optimize materials and construction techniques to achieve better thermophysiological comfort. The paper also addresses the limitations of current testing methods and proposes future directions for research, including the integration of advanced sensors and data analytics to enhance the accuracy and applicability of manikin-based evaluations.

Conclusions suggest that thermal sweating manikins are invaluable tools for optimizing garment design and improving thermophysiological comfort. Their ability to provide consistent and reproducible results under controlled conditions makes them superior to traditional human trials, which can be influenced by numerous variables. As the demand for high-performance clothing continues to grow, the role of thermal sweating manikins in research and development is expected to become increasingly significant.

Keywords: Thermal Manikin, Sweating, Clothing Insulation, Evaporative Resistance, Thermophysiological Comfort

Experimental Study on the Influence of Activity Intensity and Personal Protective Clothing on Human Thermal Responses in Dynamic Hot Environments

Mengyao Huang (Tsinghua University)
Ming Fu (Anhui Province Laboratory of Human Safety, Hefei Institute for Public Safety Research, Tsinghua University)
Jia Wang (Tsinghua University)
Liangchang Shen (Anhui Province Laboratory of Human Safety, Hefei Institute for Public Safety Research, Tsinghua University)
Yayun Li (Anhui Province Laboratory of Human Safety, Hefei Institute for Public Safety Research, Tsinghua University)
Xuefan Wang (Anhui Province Laboratory of Human Safety, Hefei Institute for Public Safety Research, Tsinghua University)
Shifei Shen (Tsinghua University)

Abstract

This study aims to investigate human thermal responses in hot environments and the possible factors that influence these responses. A subject experiment was conducted in a dynamic hot environment, with temperatures fluctuating between 25°C and 35°C. Varying activity intensities of 4 km/h and 7 km/h and three different clothing conditions, including basic clothing, firefighting clothing, and rescue clothing, were also taken into consideration. The main thermophysiological indicators were measured, and the perceptual performance was assessed. The results indicate that increases in ambient temperature and activity intensity can significantly heighten thermophysiological pressure and cause thermal discomfort and fatigue. Wearing high thermal-resistance clothing exacerbates this effect, resulting in elevated levels of heat strain. Implementing intermittent rest periods can substantially improve thermal responses, reducing the heat strain index in terms of physiology and perception by 60% and 93%, respectively. Nonetheless, recovering core temperature requires additional measures. The thermal sensation and thermal comfort under protective clothing conditions statistically correlate with the mean skin temperature. Overall, this study is valuable for assessing thermal safety and thermal comfort and developing corresponding predictive models for occupational heat exposures.

Keywords: dynamic hot environment, activity intensity, personal protective clothing, thermal response, subject experiment

Influence of Different Fabrics on Cutaneous Thermal Sensation Under Radiant Heat Exposure in Electric Vehicles During Winter

Sang-Hyun Roh (Seoul National University)
Suhyeon Yeom (Seoul National University)
Joo-Young Lee (Seoul National University).

Abstract

To reduce electricity consumption in electric vehicles (EVs) during winter, the development of an in-vehicle localized proximity heating system is being carried out. Car manufacturers are integrating radiant heaters into the vehicle's trim to provide heating according to passengers' needs. However, the risk of skin burns due to prolonged unconscious exposure cannot be ignored. In particular, thermal thresholds on the skin may vary depending on the material of the clothing. Therefore, we explored differences in the perceived warmth, hotness, and heat pain thresholds based on the material of the clothing. The present study consisted of two different experiments. [Experiment 1] Eight males (age: 24.1 ± 3.9 y, height: 178.2 ± 5.7 cm, weight: 74.1 ± 15.6 kg) participated in two conditions: (1) bare skin, and (2) 100% cotton pants. The lateral side of the thigh was exposed to a radiant heat panel (10 × 30 cm2, 130oC surface temperature) at a 2 cm distance. The climate chamber was maintained at 14.3 ± 0.2oC and 57 ± 1%RH to simulate the interior environment of vehicles parked during winter. [Experiment 2] Seven males (23.8 ± 2.6 y, 175.1 ± 4.3 cm, 81.0 ± 10.5 kg) participated in the following three conditions: (1) 100% cotton, (2) 100% wool, and (3) 100% polyester pants. The identical body region on the left thigh was exposed to the radiant heat panel (10 × 30 cm2, 135oC surface temperature) at a 10 cm distance, which was the typical distance between the passenger and a thigh heater inside the EV. The climate chamber was maintained at 21.9 ± 0.2oC and 50 ± 1%RH. As a result, cutaneous thermal thresholds showed no significant differences between bare skin and clothed conditions. The cutaneous thermal thresholds for perceiving thermal sensation on the thigh did not differ among the cotton, polyester, and wool pant conditions. Interestingly, the heat flux at the point where thermal thresholds were achieved was the lowest, and the surface temperature of the fabric was the highest for the cotton condition. There was no significant difference in heat flux or surface temperature between the polyester and wool pant conditions.

Keywords: Cutaneous thermal sensation, Radiant heat, Clothing, Fabric

Comfort of PPE – How can Comfort Assessment be Integrated in a General PPE Standard?

Edith Classen (Hohenstein group)

Abstract

The determination of comfort of clothing is done using with different test methods and the comfort of clothing can be evaluated. This comfort evaluation is mostly done under standardized methods which simulated the environmental use condition. The test methods are material test methods or product test methods (e.g. ISO 11092, ISO 15381). Results of subject trials are available which confirm that the results of these methods meet the real conditions of use. The evaluation of the comfort of personal protective clothing is often limited because the protection function, often material layers with certain functions are used for safety reasons and these combinations reduce the comfort of such clothing. Personal protective clothing should provide the protection against certain risk (e.g. fire, cold) and at the same time provide the highest comfort as possible for the user. The international standard ISO 13688 specifies the general requirements for protective clothing. These requirements relate to the ergonomics, harmlessness, aging, size designation, and compatibility of protective clothing. This standard is under revision and one important issue is the integration of requirements of comforts properties. Up to now, there are no general requirements for the comfort assessment of PPE available. In some PPE product standards material measurements are required, other product standards use product measurement with manikins. Another important aspect for the PPE testing is the economic situation. Are the existing methods applicable for the assessment of the comfort of PPE? Is it necessary to adapt methods for the situation of the user of PPE? The talk will give an overview about the current discussion in the PPE standardization group to improve PPE by including an adequate test scenario to evaluate the comfort of different personal protective clothing.

Keywords: PPE, comfort, test methods, PPE standardization

Development of Improved Liquid Cooled Garment

Pratibha Sinha (US Army)

Abstract

Impermeable suits protect wearers from Chemical, Biological, Radiological, and Nuclear (CBRN) hazards, but they retain body heat, which has been a concern of the Department of Defense (DoD) for some time. While the concept of a cooling vest in this context is not new, existing personal cooling apparels are incompatible and/or inefficient when used with CBRN protective suits. Excessive exposure to high thermal loading can lead to a multitude of adverse effects, beginning with cognitive problems and progressing through heat exhaustion, cramps, heat stroke, and eventually cardiac arrest. To avoid thermal injury, Warfighters limit their time wearing impermeable protective suits when managing a CBRN event, but this approach can reduce mission length and affect achieving operational objectives.

To address this challenge, Oceanit under the Small Business Innovation Research program funded by DEVCOM SC, Joint Science and Technology Office for Chemical Biological Defense (JSTO-CBD) and Air Warrior has developed one of the most effective FR Liquid Cooled Garments (LCG) in the market today. Oceanit's LCG is a form-fitting garment with a network of thermally conductive tubing that extracts body heat and can be worn under all authorized personal protective equipment and chemical/biological protective clothing. Oceanit specifically designed and developed ThermoCore®, a thermally conductive polymer, for use in this apparel optimizing the product for thermal conductivity, mechanical properties, manufacturability, and performance temperatures. The fabrics, the design, and the tubing layout was designed and developed to fit the target population with just four sizes instead of five, thus potentially reducing the DoD logistical burden. Further, the custom components developed are modular and can be used to add accessories such as balaclava, shorts, sleeves, or pants to the vest to add further cooling capacity to the individual Warfighter.

Thermal Manikin tests were conducted in accordance with the ASTM test method, ASTM F2371, Standard Test Method for Measuring the Heat Removal Rate of Personal Cooling Systems Using a Sweating Heated Manikin, in an environmental chamber at USARIEM using a 20-zone sweating thermal manikin. Manikin test results have shown that Oceanit's LCG provides significantly higher heat extraction under the same environmental conditions than the currently fielded Environmental Control Vest (ECV), while at the same time reducing the weight. The LCG vests performed nearly 30% better in extracting body heat while weighing 15% less than the ECV. With a higher heat extraction rate, Warfighters will need to carry fewer batteries, further lessening their physiological and logistical burden. Human Factors Evaluation of the LCG vests were conducted at DEVCOM SC to assess any restrictions in mobility. The LCG can be seamlessly integrated into any protective garment using a cooling vest such as such as the JSTO-CBD funded S&T developing system, the Tactical All-Hazards Ensemble. The technology developed from this effort will transition to the Uniform Integrated Protective Ensemble Family of Systems program of record under the existing Technology Transition Agreement. This presentation will show the benefits of the LCG in terms of thermal extraction performance, form factor, and reduced weight while meeting all the requirements of the ECV.

Keywords: Thermal, Manikin, Microclimate, Cooling, Conductive, tubing

An Evaluation of Thermal Insulation of Protective Gear on Firefighter Heat Strain

Mushfika Mica (North Carolina State University)
Emiel Denhartog (North Carolina State University)
Roger Barker (North Carolina State University)
Anthoney Deaton (North Carolina State University)

Abstract

Between 2019 and 2024, 122 incidents occurred in the USA where firefighters were shot and killed while responding to active-shooting scenarios. After firefighters became targets of violence, fire departments requested funds to make ballistic vests standard personal protective equipment (PPE). Wearing ballistic vests with turnout gear may not only increase the risk of heat strain by reducing heat dissipation but also contribute to discomfort, restricting movement and increasing sweat accumulation due to increased thermal insulation. Thermal insulation measures the ability of a material or system to reduce the transfer of heat.

To quantify the thermal insulation, six firefighting ensembles were tested using thermal male manikin: E1) station uniform; E2) station uniform+ballistic vest; E3) station uniform+turnout suit; E4) station uniform+turnout suit+ballistic vest worn under turnout jacket; E5) station uniform+turnout suit+ballistic vest worn over turnout jacket; E6) station uniform+turnout suit+ballistic vest with hard plates.

The thermal insulation (Rt) values for E1, E2, E3, E4, E5, and E6 in the torso area were 0.166, 0.331, 0.463, 0.622, 0.652, and 0.631 $m2 \cdot °C \cdot W-1$ respectively. The results evidently depicted a progression of thermal insulation values in the torso area with adding layers. Rt increased from 0.166 $m2 \cdot °C \cdot W-1$ in E1 (baseline-without ballistic vest) to 0.331 $m2 \cdot °C \cdot W-1$ in E2 (with ballistic vest added).

The relative increase in Rt from E1 to E2 is approximately 99%, which indicated twice the thermal insulation with the addition of the ballistic vest. The further increase in Rt through E3 to E6 up to 0.652 $m2 \cdot °C \cdot W-1$ demonstrated the compounding effect of additional layers in the firefighting turnout ensemble. The substantial increase in Rt from E1 to E2 is due to the dense materials in ballistic vests that is designed to provide ballistic protection that inherently reduced heat transfer. The further increase in Rt through E3 (baseline-without ballistic vest) to E6 was caused by the added layers of turnout suits. The additional layer of ballistic vest in E4, E5, and E6 increased the thermal insulation further. Despite adding hard plates to the ballistic vest in E6, it had a Rt of 0.631 $m2 \cdot °C \cdot W-1$ which is lower than E5. It indicated that adding hard plates reduced air gaps and created more contact points for heat transfer which led to the lowering of thermal insulation of E6.

Keywords: firefighter, heat strain, ballistic vests, turnout gear, thermal insulation

Evaluation of Thermal Resistance in Infant Garments and Clothing Ensembles Using a Baby Thermal Manikin

Takako Fukazawa (Kyoto University of Education)
Yutaka Tochihara (Kyushu University)
Sachiyo Ikeda (Fukuoka Women's University)
Seon Suk Kim (Kyungpook National University).

Abstract

In this study, we aimed to obtain insights that contribute to the development of thermally comfortable clothing environments for infants by examining seasonally appropriate clothing levels. A baby thermal manikin, designed to replicate not only the body shape of a 0.5-year-old infant but also metabolic heat production and skin surface temperature, was employed for the evaluation. With the cooperation of a kindergarten and a nursery school in Higashi Ward, Fukuoka City, Japan, a year-long field survey was conducted on the clothing conditions of 16 infants aged approximately 0.5 to 1 year. Based on the survey results, the thermal resistance of 15 infant clothing ensembles was measured using the baby thermal manikin. From these measurements, an estimation formula was developed to predict the thermal resistance of clothing ensembles based on total garment weight. Using this formula, the thermal resistance of the infants' actual clothing ranged from 0.53–0.81 clo in summer, 0.42–1.33 clo in autumn, and 1.03–1.90 clo in winter. Under the environmental conditions recorded during the study, the thermal resistance required to maintain thermal balance in resting infants was estimated to be approximately 0.3 clo in summer, 0.5 clo in autumn, and 0.8–1.8 clo in winter. These findings suggest that while the infants were generally dressed appropriately in winter, there was a tendency toward overdressing in summer and autumn, particularly in autumn.

Keywords: infant's clothes, heat transfer, clothing thermal resistance, baby thermal manikin

Colorants as Green Functional Agents for Environmentally Friendly Personal Protective Textiles

Gang Sun (University of California, Davis)
Yufa Sun (University of California, Davis)

Abstract

Novel personal protective textiles can provide various functions such as antibacterial, antiviral, self-cleaning, UV-protective, detoxifying, fire, and thermal protection for different professions and the public with advanced technologies. Many of the functions are currently achieved by incorporating reactive functional agents into polymers or fibers, especially in the development of active chemical and biological protective materials. The use of these chemical agents in textile products with close skin contacts and respiratory access could bring human safety concerns, and production and disposal of such materials may have environmental consequences. Thus, the adaptation of green chemistry and sustainable technologies in the development of personal protective textiles has been highly desired and a challenge to researchers. In recent years, we have been exploring the possibility of employing colorants as functional agents and daylight as a driving force in design and preparation of light-induced functional fibers and polymers. These colorants could be traditional textile dyes or pigments and can be edible vitamins with colors. The unique features of these chemicals are that they are photosensitizers, and the reactive functions are fully based on exposure to daylight without additional energy inputs. This presentation will illustrate the photochemistry of colorant photosensitizers and provide several successful examples of light-induced functional fibers and textiles.

Keywords: Chemical and biological protective, Photosensitizers, Colorants, Sustainable

Performance of a Thermode with an Integrated Pressure Sensor for Use in Human Cutaneous Temperature Sensitivity Assessments

Inderpreet Bains (Laboratory for Exercise and Environmental Physiology, Simon Fraser University)
Jingkai Pang (Laboratory for Exercise and Environmental Physiology, Simon Fraser University)
Dora Wc Hsiao (Laboratory for Exercise and Environmental Physiology, Simon Fraser University)
Clara V Etter (Laboratory for Exercise and Environmental Physiology, Simon Fraser University)
Matthew D White (Laboratory for Exercise and Environmental Physiology, Simon Fraser University)

Abstract

Cutaneous temperature sensitivity thresholds (CTST) can be assessed by application of a thermode probe on the body surface. Variations in body surface application pressure of thermodes is a source of variability for CTST. To allow for the control of surface application pressure during CTST assessments a thermode probe was constructed with force sensing capability. PURPOSE: To develop a reliable thermode probe with the ability to control thermode application force during cutaneous temperature sensitivity testing in humans. METHODS: Two force sensing resistors were mounted in series on a thermode probe. Known weights to give forces of 1.47, 1.96, 2.94, 3.92, and 4.90 N were used in across trials to evaluate the force sensing capabilities of the sensor and to subsequently permit assessments CTST at given application forces. ANALYSIS: Bland-Altman plots were used to test for agreement between trials and intraclass correlation coefficients were employed to assess reproducibility between the five forces with each of resistance and conductance. RESULTS: Bland-Altman plots revealed differences between trial 1 and trial 2 for resistance and conductance that were not significantly different ($p>0.05$) and when each was plotted against 2-trial differences this gave linear regression coefficients that were not significant ($p>0.05$). Intraclass correlation coefficients among 5 trials for each of resistance and conductance at 1.96 N were high and significant ($0.93 < r < 0.99$; $p<0.05$). CONCLUSION: For assessing cutaneous temperature sensitivity thresholds, a novel thermode probe with integrated force sensing resistors was developed that produced trial-to-trial values that were both in agreement and reproducible.

Keywords: cutaneous surface pressure, temperature regulation, thermosensitivity

Two-Dimensional CFD Simulation of Steady-State Dry Heat Loss from a Clothed Human Torso Using Fabric-Covered Cylindrical Models

Zubieda Alali (PhD student at Kansas State University)
Steven Eckels (Faculty member at Kansas State University)

Abstract

By integrating CFD modeling with fabric property characterization, this study offers a practical and precise tool for evaluating clothing systems. Ultimately, these simulations contribute to refining the selection of fabric transport properties to ensure thermal comfort while providing adequate protection. Understanding thermal transport in clothing systems is essential for enhancing human thermal comfort and protection across various environmental conditions. This study proposes a two-dimensional computational fluid dynamics (CFD) model to simulate steady-state dry heat loss from a clothed human torso. The model utilizes fabric-covered cylinders as realistic alternatives for human body segments, providing a computationally efficient and experimentally feasible geometry to examine heat transfer mechanisms in clothing systems.

Fabric-covered cylinders effectively represent clothing assemblies, capturing critical features such as fabric-air layering, thermal insulation, and surface curvature. This geometric simplification offers a well-defined experimental and computational framework, allowing for thorough analysis without the high computational costs associated with accurately modeling clothed human figures. While substantial progress has been made in modeling the true geometry of clothed human bodies, the significant computational expense of such simulations restricts their use for research studies that look at different variables.

In this research, the CFD model is compared to laboratory evaluations, including hot plate measurements and thermal manikin tests conducted in environmental chambers. Material properties such as thermal conductivity and fabric structure were incorporated into the model. Simulations were conducted with a constant cylinder surface temperature of 35 °C—representative of human skin—against an ambient air temperature of 5 °C. External air velocities ranging from 0.05 to 6 m/s were considered to capture convective effects under still and windy conditions. The model also integrates thermal radiation heat transfer within the fabric and air gap to create a realistic total heat transfer mode. The fabric layer was modeled as a porous medium to realistically account for its complex internal structure. The bare cylinder case was included as a baseline for validation, with results demonstrating strong alignment with classical heat transfer correlations for crossflow over heated cylinders.

Simulation results indicated that, across a wide variety of clothing fabrics, the thermal resistance to dry heat transfer scales proportionally with fabric thickness, consistent with previous literature findings. Furthermore, the simulations provided valuable insights into the impact of air gaps and varying spacing between the fabric and skin surface, which significantly affect heat transfer efficiency. These findings support the continued utilization of fabric-covered cylinder models as effective substitutes for more complex geometries in the study of clothing thermal performance.

Additionally, the model allows for direct comparison with standardized thermal insulation values (clo units), which range from 0 clo (nude body) to approximately 2 clo for ensembles such as the standard U.S. Army uniform, as referenced by ASHRAE and other thermal comfort guidelines.

Assessment of a Heated Base Layer when worn with Subzero Warfighter Ensembles at –20°C Utilizing a Dynamic Heat Flux Thermal Manikin

Meredith McQuerry (ThermaNOLE Comfort Lab®, Florida State University)
Josephine Bolaji (ThermaNOLE Comfort Lab®, Florida State University)
Xiaojian Xu (Thermal and Mountain Medicine Division, U.S. Army Research Institute of Environmental Medicine)
Madeline Poley-Bogan (ThermaNOLE Comfort Lab®, Florida State University)

Abstract

The purpose of this research was to determine the efficacy and performance of a heated clothing base layer system when worn with three subzero cold weather military ensembles in different environmental conditions. First, the baseline thermal properties of the heated base-layer (heat off), and the three ensembles (each worn over the unpowered base layer) were measured. In the present series of evaluations, the three cold weather ensembles (light, intermediate, and cold) were worn with a heated base-layer (Human Systems Integration (HSI), East Walpole, MA) and measured to determine the heating power provided by the wearable heating system. Each ensemble was tested on an ANDI dynamic thermal manikin (Thermetrics, Seattle, WA) in a –20°C environment while the active heating system was turned on at power levels of low, medium, and high. The heat gains, i.e., the heat from the HSI heated layer to the manikin, ranged from approximately 25 W to 48 W. This heat was distributed to four body regions: torso, thighs, hands, and feet. To the researchers' knowledge, this project was the first of its kind to measure the heat gain of a wearable clothing system while wearing a subzero warfighter ensemble utilizing a dynamic thermal manikin.

Keywords: Manikin, Subzero, Wearable Technology, Heat Transfer, Warfare

Understanding Glove Manual Performance in Commercial Fishing: Insights from Simulated Wet Testing

Leslee Weible (Iowa Statue University)
Mengying Zhang (Iowa State University)
Rui Li (Iowa State University)
Guowen Song (Iowa State University)

Abstract

Introduction. Commercial fishing is one of the most hazardous occupations, but there is very limited information about personal protective equipment (PPE) that can help to minimize the risks involved. Though researchers have investigated gloves from other industries, a critical gap exists in understanding glove effectiveness under the wet, slippery conditions common at sea. This study aims to address the knowledge gap by evaluating manual performance of fishing gloves in simulated wet versus dry task conditions.

Methods. Participants between the ages of 18-55 with no prior hand/arm injuries were recruited to this IRB approved study (24-205-00). Two commercially available gloves, nylon-shell glove with rubberized grip and a neoprene-based glove with textured palms (Glove 1 and Glove 2 respectively), were tested in wet and dry conditions for this study. Wet testing was facilitated by having the participants submerge their hands in 22±2°C water for ten seconds prior to completing the task. Four tasks were performed in a randomized order: the modified pegboard test, a pull strength test, torque strength, and grip strength.

Results. Overall, wet conditions impaired performance relative to dry conditions. On average, pegboard test times were slower in wet conditions and Glove 2 performed approximately 2.50-4.00% faster completion times than Glove 1. Torque strength decreased under wet conditions for both gloves. Grip strength slightly increased in wet conditions by around 0.50-2.75%, with Glove 2 outperforming Glove 1. Dry conditions resulted in higher pull strength overall. When comparing between the gloves, Glove 1 yielded better results for pull strength in wet conditions and Glove 2 surpassed Glove 1's performance in dry conditions.

Conclusion and Future Directions. Wet conditions significantly degraded manual performance of the participants, highlighting the importance of evaluating PPE under realistic conditions to ensure occupational safety. The findings underscore that selecting gloves suited to specific tasks and environments can mitigate performance losses and improve worker safety in commercial fishing. Future research should expand testing to a wider range of glove designs and materials and diverse environmental conditions (e.g., varying wetness levels and temperatures) to inform more effective PPE selection and ergonomic best practices.

Keywords: personal protective equipment, manual performance, commercial fishing, wet environment, glove

Impact of humidity on the Thermal Resistance of Ski Gloves

Yazid Kaced (Decathlon SportsLab)

Abstract

While a lot of work has been carried out in determining the thermal properties of textile materials, much remains to be investigated when examining how moisture content affects the thermal resistance (Rc) of finished products.The main goal of this work is to address this research's gap by evaluating how sweating influences the ski glove's thermal resistance (Rc).

The test is conducted under two different conditions: dry (measuring thermal resistance via dry gloves) and wet (measuring total heat transfer in gloves with artificial sweating). The test conditions are: 5°C ambient temperature, 30°C hand temperature, 55% relative humidity, and 3.33 $m.s^{-1}$ wind speed. The rate of sweating is set at 200 $ml.m^{-2}.h^{-1}$ (approximately 85 ml over a period of 7 to 8 hours), which represents average hand sweating rates during physical exertion.

To determine the Rc of wet gloves appropriately, we use a thermal balance method in this study. We measure the total amount of water used and the amount remaining in the glove after the experiment. The difference between these two represents the amount of water evaporated. From this evaporated water amount, we determine the evaporative flux with evaporative flux being distinguishable from total heat flux. Evaporative component was calculated through the formula: Evaporative Flux = m·Cp, where "m" is the rate of water vaporization ($kg.s^{-1}$) and "Cp" is the water specific heat during the vaporization phase ($kJ.kg^{-1}\cdot K^{-1}$).

The results show a significant reduction in thermal resistance that was evident when the glove was saturated, a maximum possible decrement of 25%. There were, however, a number of drawbacks found: inability to measure wet thermal resistance across various areas, difficulty measuring higher flow rates in accordance with water runoff, and a longer time required in order to generate sufficient amounts of water to reach a steady state condition.

Future studies should include longer test durations to obtain more data on water uptake, measure water capacity of a glove, and determine the relationship between water content and lower Rc in a range of glove types.

Keywords: Thermal resistance, Sweating thermal manikin, Protective gloves, Humidity effect, Thermal comfort

Analysis of Thermal Efficiency in Phase Change Cooling Vests with Variable Melting Points

Miriam Martinez-Albert (Textile Industry Research Association-AITEX)
Eva Bou-Belda (Universitat Politècnica de València)

Abstract

The thermal comfort of workers in outdoor environments is influenced by various factors, including environmental conditions, clothing choices, and the specific tasks being performed. Employees who work outside are at a higher risk of experiencing thermal stress in extreme weather conditions that are beyond their control. In situations with high temperatures and heat stress, personal cooling garments can be crucial for helping the body manage excess heat by reducing core and mean skin temperature. There are several types of cooling garments available on the market, and their effectiveness largely depends on the cooling mechanisms they utilize. The most common cooling mechanisms include air cooling garments, liquid cooling garments, evaporative cooling garments, phase change cooling garments, and hybrid cooling garments. Currently, a standard exists for assessing both the cooling power and cooling duration of these garments; however, there is no consensus in the literature on how these two factors affect user comfort. This study investigates the relationship between cooling power, cooling duration, and the working temperature of phase change material (PCM) cooling vests, focusing particularly on their melting point and how it influences the thermal sensation and comfort experienced by users. To facilitate this evaluation, we have developed an innovative laboratory testing method that combines a thermal manikin with a computer simulation program designed to replicate the user's thermoregulatory system. The findings indicate a significant relationship between the melting temperature of the PCM cooling vest, its cooling duration, and cooling power, as well as their effects on the user's thermal sensation and comfort.

Keywords: cooling vests, cooling garments, thermal comfort, personal cooling systems, thermal manikin

Investigating the Market: Sizing and Fit Limitations in Firefighting PPE for Female Firefighters

Yingying Wu (Kansas State University)
Celeste Graciano (Kansas State University)

Abstract

As female representation within the firefighting workforce steadily increases, the inadequacies of existing personal protective equipment (PPE) – specifically in terms of sizing and fit – are gaining critical visibility. Historically designed to accommodate male body types, standard turnout gear often fails to meet the physiological and ergonomic needs of female firefighters, leading to safety concerns, discomfort, and reduced operational performance. This study presents a comprehensive market analysis that investigates the extent to which current firefighting turnout coats and pants address these gender-specific requirements.

Utilizing qualitative research methods, the researchers conducted a targeted market review of five major fire service PPE manufacturers: Globe, Lion, Honeywell, Fire-Dex, and CrewBoss. The study examined product specifications, fit options, material choices, and the extent of adherence to NFPA 1971 certification standards. Particular attention was paid to online communications, catalog descriptions, and availability of female-specific sizing systems. It was found that despite all brands claiming compliance with NFPA 1971, there was a pervasive lack of gear explicitly tailored for the female form. Specifically, Globe was the only manufacturer that consistently mentioned a "Women's" fit option, yet failed to clearly define how it differed from regular or male-oriented fits. Besides, our findings underscore a significant design gap: most turnout coats lack shaping around the bust, and turnout pants frequently feature low-rise designs ill-suited for the waist-to-hip proportions of female firefighters. These challenges, corroborated by previous research, demonstrate the urgent need for gear that accommodates female anthropometry. Thus, this study advocates for new female-specific PPE design centering on female body shape and function. The results also support a broader industry push for the development and standardization of female-specific turnout gear. It is crucial not only for ensuring personal safety and comfort but also for fostering retention within the firefighting profession. The research holds implications for gear manufacturers, fire departments, and standard-setting bodies like the NFPA, urging immediate reconsideration of current PPE frameworks to support a diverse and evolving workforce.

Keywords: Female firefighters, Firefighting PPE, Fit and sizing, Market analysis

Characterizing localized thermal insulation of gloves at the fingertip using a sensor-integrated hand manikin and infrared thermography

Mengying Zhang (Iowa State University)
Rui Li (Iowa State University)
Jie Yang (Xi'an University of Science and Technology)
Fan Zhou (Iowa State University)
Yulin Wu (Iowa State University)
Guowen Song (Iowa State University)

Abstract

Effective hand protection in cold environments requires accurate evaluation of glove thermal insulation. However, traditional thermal hand manikin typically measures only the overall thermal resistance for an entire finger, failing to capture variations across the finger. Fingertips, in particular, experience the greatest heat loss and often exhibit the lowest temperatures, making them especially vulnerable to cold injuries. Therefore, a more detailed measurement, focusing on the fingertip, is needed to guide glove design optimization, enhance dexterity, and prevent cold injuries.

This study introduces a novel approach using a sensor-integrated thermal hand manikin to quantify local insulation at the fingertip. Flexible miniature heat flux and temperature sensors were placed on the nailbed and the distal, middle, and proximal phalanges of the manikin's little finger. Simultaneously, infrared (IR) thermography recorded the external surface temperature of the gloved finger. The thermal hand manikin maintained a constant surface temperature of 35 °C during the experiment, generated heat flux was recorded as well. Thermal data from the embedded sensors and the IR thermography was used to calculate sectional thermal insulation across the finger sections.

Infrared thermography revealed significant temperature differences along the finger: the distal phalanx had a markedly lower surface temperature than the middle and proximal phalanges, indicating greater heat loss at the distal phalanx section. The nailbed was even colder than the distal phalanx, identifying it as the region of highest heat loss. Significant differences in insulation across the finger section. The nail bed and distal phalanx consistently showed lower thermal resistance than the middle and proximal phalanges. This indicates that the fingertip sections are less insulated and lose heat more rapidly under a glove, confirming long-suspected vulnerabilities in glove coverage.

Combining embedded sensing with IR imaging provides a high-resolution, non-invasive method to assess localized glove thermal performance. By identifying areas of reduced insulation at the fingertips, this integrated technique enables targeted improvements in glove design and engineering to reinforce insulation in these vulnerable regions. This targeted improvement helps prevent cold-induced injuries and preserves manual dexterity by optimizing the balance between thermal protection and flexibility.

Keywords: Thermal resistance, hand manikin, glove design, heat flux sensors, cold weather injury

Breaking the Fit Barrier: Failures in Anthropometric and Patternmaking Applications for PPE Sizing

Kayna Hobbs-Murphy (Colorado State University)

Abstract

Personal Protective Equipment (PPE) is critical to worker safety across industries, yet much of it continues to be designed and sized based on outdated and narrow body standards. Research has consistently shown that ill-fitting PPE increases injury risk, particularly among women, larger-bodied workers, petite workers, and disabled workers. However, structural factors within manufacturing and supply chains have limited progress toward more inclusive sizing practices. This paper examines the consequences of persistent sizing gaps in PPE and outlines the technical expertise required to address them. Drawing from professional domains including apparel patternmaking, garment technology, anthropometrics, and occupational health and safety, the analysis demonstrates how translating body diversity into functional protective equipment demands specialized skills across measurement, design, and ergonomic assessment. Improving PPE fit across diverse body types is both a technical and structural challenge, requiring the integration of precise knowledge at every stage of design and production to ensure equitable and effective worker protection.

Keywords: PPE, Anthropometry, Apparel Patternmaking, Sizing Systems, Occupational Health and Safety

Physical and Physiological Properties of Waterproof and Breathable Jackets with PFAS-free Membrane

Suhyeon Yeom (Seoul National University)
Ho-Joon Lee (Seoul National University)
Sang-Hyun Roh (Seoul National University)
Do-Hyung Kim (K2 Korea)
Joo-Young Lee (Seoul National University)

Abstract

PFAS, used for water repellency in outdoor clothing, do not naturally degrade and can accumulate in the human body through soil and other environmental pathways when outdoor gear is discarded. This accumulation is known to potentially disrupt hormones, suppress the immune system, and increase the risk of cancer. Various outdoor clothing incorporating PFAS-free water-repellent technologies have been developed and are currently available on the market. However, evaluations of the wearability of these products remain limited. Therefore, we collected commercially available PFAS-free outdoor jackets and examined their physical properties and physiological responses through human wear trials. Firstly, using a thermal manikin (Newton, 20-zones), we analyzed the physical properties of four water-resistant and breathable jackets using PFAS membranes (Salomon, Florence, Kolon, and K2) and three jackets using PFAS-free membranes (Patagonia, Arcteryx, and K2). Secondly, we selected four of the seven jackets (one PFAS-based, and three PFAS-free) for human wear trials in a climate chamber. Eight males participated in the four jacket conditions (age 27.4 ± 3.6 y, height 173.8 ± 4.8 cm, and weight 71.5 ± 6.1 kg), and a trial consisted on 10-min rest, 30-min exercise, and 20-min recovery). Despite differences in jacket masses (276 to 717 g), there were no marked differences among the jacket types (Icl: 0.300–0.388 clo, Re,t: 0.048–0.057 kPa·m²/W). Human wear evaluation also revealed no significant differences among the four jacket conditions in auditory canal temperature, mean skin temperature, heart rate, thermal sensation, and thermal comfort. In summary, there were no notable differences in the physical or physiological characteristics of commercially available outdoor jackets regardless of whether they used PFAS or PFAS-free membranes. These results suggest that wearing environmentally friendly PFAS-free jackets may not negatively affect wearing comfort when comparing to outdoor jackets with PFAS membrane.

Keywords: Water repellency, Thermal insulation, Core temperature, Human wear trial

Heat Flux Generated versus Heat Flux Measured: A Backside Cooling Experiment using a Dynamic Thermal Manikin to Measure Heated Garments

Meredith McQuerry (ThermaNOLE Comfort Lab®, Florida State University)
Rick Burke (Thermetrics)
Xiaojiang Xu (Thermal and Mountain Medicine Division, U.S. Army Research Institute of Environmental Medicine)
Madeline Poley-Bogan (Thermal and Mountain Medicine Division, U.S. Army Research Institute of Environmental Medicine)
Josephine Bolaji (ThermaNOLE Comfort Lab®, Florida State University)

Abstract

Recently developed dynamic thermal manikins provide the capability of measuring heat gain, in addition to traditional measures of heat loss through clothing. When experiencing an external heat load, such as environmental temperatures above 35°C, radiant solar exposure, or direct applications via wearable technology, dynamic heat flux sensors along the manikin's carbon epoxy shell enable direct measurements of heat flux as opposed to relying on heat flux generated power calculations. To overcome previous issues with heat loads causing internal manikin sensors to overheat and shut down, a backside cooling system was implemented, internal to the manikin, to remove excess heat and avoid manikin sensor shut off. To validate this novel mode of operation, three cold weather ensembles were tested at -20°C, in conjunction with a heated base layer garment, on an ANDI dynamic thermal manikin (Thermetrics, Seattle, WA, USA), with and without backside cooling enabled. A 5-minute block average report was saved at four intervals: immediately prior to heating and at the end of heating at power levels 1 (low), 2 (medium), and 3 (high). The instantaneous power difference (H Diff, Watts) was calculated for each zone (current heat flux at levels 1, 2, or 3 – reference heat flux with no heating), with surface area considered. Total Heat Difference (H Diff) was computed as the sum of all manikin zones, as well as the sum of all zones covered by heating elements. When comparing cooling conditions, heat flux measured demonstrated greater alignment between the two test conditions, as they were less affected by environmental disturbances and internal manikin surface temperature variability. However, overall findings indicate the addition of cooling provides more consistent and stable results across the test duration as it allows all heaters to operate in their active control region and no manikin overheating occurs. Future work should include an expansion of this pilot study to include other types of ensembles, environmental conditions, and external heat loads.

Keywords: Thermal manikin, Heat flux, Validation, Heat load, Active cooling

Maximum Skin Wettedness While Wearing Woven and Non-Woven Clothing

Thomas Bernard (University of South Florida)
George Havenith (Loughborough University)
Candi Ashley (University of South Florida)

Abstract

Introduction. Maximum skin wettedness (wmax) is the ratio of required evaporative cooling (Ereq) divided by maximum evaporative cooling (Emax) at the upper limit of thermal equilibrium. In the semi-nude case, wmax has reported values between 0.2 and 1.0 depending on ambient water vapor pressure, acclimatization state, metabolic rate, fitness, and age. While wmax occurs at maximum rate of sweating at low evaporative resistance, this paper reports on wmax while wearing different clothing ensembles that cover most of the body.

Methods. A progressive heat stress protocol identified the critical environment at the upper limit of thermal equilibrium. The 445 observations included five clothing ensembles (shorts and tee shirt plus woven shirt and trousers, woven coveralls, nonwoven particle-barrier coveralls, nonwoven microporous water-barrier coveralls, and nonwoven vapor-barrier coveralls) at metabolic rates from 130 to 500 W and at three humidity levels (20, 50 and 70% RH). The resultant total insulation and resultant total evaporative resistance from manikin data were used to compute Ereq, Emax, and wmax. A linear mixed model was fit to the 445 observations. Metabolic rate was a continuous variable, RH level and Ensembles were fixed effects, and participants were a random effect.

Results. wmax increased with metabolic rate. There was a difference among ensembles where wmax for vapor-barrier at 1.80 was higher than the other ensembles at 1.45. wmax changed across the three humidity levels, where 20% was 1.18, 50% was 1.59, and 70% was 1.78. There was no interaction between RH and Ensembles.

Conclusions. wmax increased with increasing metabolic rate, increasing ambient humidity, and for high evaporative resistance (i.e., vapor-barrier coveralls over the other woven and nonwoven ensembles). Importantly, wmax was consistently greater than 1, which means the skin was fully wetted for maximum surface coverage. While wmax represents a physiological limit in the seminude case, it represents additional distribution of sweat beyond the skin to the clothing and more complex pathways for overall cooling as well as loss of water due to dripping.

Keywords: Skin wettedness, Nonwoven clothing, Thermal equilibrium

Assessment of Posture and Mobility to Improve the Outer Layer Design of Korean Military Cold Weather Jackets

Ho-Joon Lee (Seoul National University),
Minhee Lee (Seoul National University)
Sang-Hyun Roh (Seoul National University)
Do-Hyung Kim (K2 Korea)
Joo-Young Lee (Seoul National University)

Abstract

This study evaluated newly designed military cold-weather outerwear using posture and mobility protocols. The mobility protocol simulated combat scenarios, including shooting, crawling, grenade throwing, and sprinting. Nine male subjects (24.4 ± 3.2 y of age, 175.6 ± 3.2 cm in height, and 74.3 ± 8.3 kg in body weight) participated in the following three clothing conditions: Control, Improved A, and Improved B. Improved A and B featured modifications in size, hood design, seams, and zippers. Posture assessments were conducted across 18 different postures. All assessments took place in an indoor facility (air temperature: 19 ± 1°C; air humidity: 45 ± 4%RH). Heart rate, clothing microclimate temperature/humidity, and subjective responses were measured. After completing all tests, subjects were interviewed using a structured questionnaire. Results revealed significant differences in arm and waist restrictions among the three conditions ($P < 0.05$), with the Control condition showing greater restriction than the two improved designs. During the mobility test, subjects reported less discomfort with Improved A compared to the other two conditions ($P < 0.05$). No significant differences were found in heart rate or trunk microclimate among the three outfits. Interview responses highlighted issues with Control, such as restricted fit, hood discomfort, impaired visibility, and insufficient length. In contrast, Improved A and B enhanced psychological comfort, suggesting potential benefits for combat and training performance. These findings underscore the importance of ergonomic and functional improvements in military outerwear to optimize operational efficiency and user satisfaction.

Keywords: Posture assessment, Mobility, Wearability, Military uniform, Cold protective clothing

Understanding Clothing Insulation in Multilayer Ensembles with the Help of Virtual Tools

Lena Parvus (Empa)
Agnes Psikuta (Empa)

Abstract

Clothing insulation is dependent on the enclosed air in the clothing system and the fabric properties. However, thermal resistance of the stagnant air is higher than that of common fabrics. The effect increases with multiple air layers in one clothing system, which is especially important for complex multi-layer clothing such as protection wear. Until now, the evaluation of parameters regarding the insulation, e.g. air gap thickness and contact area be-tween body and garment, was often done using 3D body scanning and post-processing soft-ware. However, this process faced various challenges, especially with multi-layer clothing and complex body postures, because the scanners cannot capture every detail, resulting in artifacts and inaccuracies. Thus, 3D simulation was used for the same procedure and showed reliability for simple clothing and body poses.

In this study we evaluated two multi-layer clothing systems in complex body postures, using the design software CLO3D and the surface inspection software Geomagic Control. The manikins of the previous study were converted to avatars and the garments were reproduced in CLO3D while the distances between avatar and garment were determined in Geomagic Control. The air gap thickness and contact area compared to the 3D scan data proved that the values concurred for most of the investigated body parts. However, the divergence in-creased with the level of complexity of the body postures. Furthermore, the distribution of inner material layers and the thermal and evaporative resistance of the firefighter jacket in four body postures were investigated. They showed significant changes when the body posture differed. The thermal and evaporative resistance also changed with different body postures and correlations were found. These findings provide knowledge about the insulation properties of multi-layer clothing and help optimize the validation of the 3D simulation software.

Keywords: clothing model, CLO3D software, thermal resistance, thermal comfort

Complementary Manikins for Detailed Heat and Mass Transfer Measurements at Human Body

Agnes Psikuta (Empa)
Zhuqiang Hu (Empa)
Stanislaw Kocik (Silesian University of Technology)
Cheng Gao (Empa)
Yan Liang (Empa)

Abstract

Demand of energy reduction and simultaneous enhancement of thermal comfort in human occupation spaces requires sophisticated tools that characterize detailed thermal processes in human proximity. Thermal manikins are frequently used for quantification of the heat and mass transfer processes at the human body surface and through the clothing with high spatial resolution corresponding to manikin segmentation. Modern and most advanced manikins count up to 35 thermal zone reflecting typical body division in human thermoregulation models and enable direct transfer of data for human simulation. On the other hand, they do not have a direct capability to differentiate between different heat transfer modes as they measure total heat transfer only.

In our lab we apply a combination of a thermal sweating manikin ANDI and a passive multi-sensor manikin – so called HVAC manikin to determine experimentally detailed heat and mass transfer at human body surface. The thermal sweating manikin ANDI is able to typically measure total heat dry exchange between the environment and the manikin heated to a temperature similar to human body. When sweating is added during the measurement, an evaporative heat loss is determined for the assumed sweat rate distribution. The conductive heat exchange occurs at the contact surface with the solid surfaces and can be quantified precisely as long as the contact surface corresponds to the manikin segmentation. If the temperature of the contact surface exceeds the manikin surface temperature, ANDI manikin can still quantify the induced heat gain thanks to its integrated surface heat flux sensor and active cooling system unlike other thermal manikins. The HVAC manikin with 46 sets of temperature, air speed and radiant heat flux monitors the proximal environment of the human body and enables experimental separation of radiant and convective heat transfer shares in a total dry heat transfer measured by ANDI manikin. The combination of both manikins gives an opportunity of experimental investigation of all heat transfer modes pre-sent in human thermal exchange with the surroundings in wide range of applications including indoor environment, transportation cabins, occupational settings, personal comfort systems as demonstrated in several study examples.

Keywords: Thermal manikin, multi-sensor manikin, human exposure, heat and mass transfer

Practical on-site Calibration for Multi-sensor Passive Manikin in Human Thermal Comfort and Safety Research

Zhuqiang Hu (Empa)
Agnes Psikuta (Empa)
René Rossi (Empa)

Abstract

High-resolution spatial and temporal measurement of air temperature and air speed around human body is critical for assessing human thermal comfort and safety in built environments, transportation cabins, and industrial workspaces. The multi-sensor passive HVAC manikin mounted with 46 pairs of air temperature and speed sensors provides an advanced tool for characterizing thermal exposure and as a data source for simulation tools for thermal physiology and thermal sensation. However, despite initial calibration by the manufacturer, systematic errors can arise due to residual heat from internal electronics, sensor placement constraints (hot-bead air speed sensor is 2 cm apart from temperature sensor), and long-term use. Since detaching sensors for calibration is impractical, an effective on-site calibration method is essential to ensure data reliability.

This study proposed a practical on-site calibration method for both types of sensors. For temperature, the manikin was placed in a climatic chamber with a stepwise temperature in-crease from 0°C to 40°C. Reference sensors positioned near the manikin sensors tracked discrepancies. Two calibration strategies were implemented: correction of sensor readings based on local sensor site temperature and correction of sensor readings to ambient temperature. For air speed, an in-house portable setup using a mini electric fan and adjustable spacers was developed and validated using reference anemometers with the individualized calibration curves for each sensor. The results indicated that temperature variations reached up to 2 °C due to residual heating of electronic elements. After calibration, 41 out of 46 sensors met the accuracy of ±0.2°C, the remaining 5 achieved±0.5°C. For air speed, discrepancies before calibration reached up to 1.40 m/s at 2.24 ± 0.07 m/s. The regression analysis confirmed a strong correlation ($R^2 > 0.96$) between manikin sensor readings and reference values, with a post-calibration accuracy of ±0.085 m/s within 0.1-2.5 m/s. Moreover, sensitivity analysis combined with the thermo-physiological model revealed that inaccuracies in air speed are the primary factor influencing thermal responses. The proposed on-site calibration method enhances the reliability of sensor data, making the multi-sensor passive manikin a more effective tool for research and practical applications in human thermal comfort and safety studies across diverse environmental settings.

Keywords: HVAC manikin, on-site calibration, air temperature, air speed, thermal comfort assessment

Balancing Performance and Accessibility: A Comparative Study of FPCm and JOS-3 Human Thermoregulation Models in Various Thermal Environments

Zhuqiang Hu (Empa)
Agnes Psikuta (Empa)
René Rossi (Empa)

Abstract

Human thermoregulation models play a crucial role in predicting physiological responses across various environmental conditions and have been widely applied in fields such as clothing and building design, occupational health and safety, and thermal comfort assessment. Among them, the FPCm model (a commercial model) and the JOS-3 model (an open-source alternative) are two of the most extensively used multi-segment models. This study comprehensively compared these two models, including their historical development, fundamental structure, passive heat transfer mechanisms, and active thermoregulatory controls. The performance of both models was systematically evaluated against experimental data from literature, covering five steady-state thermal conditions (cold, cool, neutral, warm, and hot), two dynamic high-temperature conditions, and two extremely cold environments requiring cold protective clothing. Results indicated that both models exhibit high predictive accuracy and reliability in simulating core and mean skin temperature. In steady-state and dynamic environments, core temperature prediction bias does not exceed 0.38°C, mean skin temperature bias remains within 1.0°C, and root mean square errors for both below 1°C. However, the FPCm model demonstrated superior accuracy under extreme cold conditions, aligning more closely with experimental data. Additionally, the FPCm model provided more accurate predictions for local skin temperatures in transient high-temperature scenarios, particularly on the forehead and hand. While both models are valuable and effective tools for thermo-physiological simulations, the study highlights their respective strengths and limitations. The FPCm model benefits from extensive validation and refinement but remains a closed-source system, limiting accessibility for modification and expansion. In contrast, JOS-3 model as an open-source system, offers greater flexibility for research, adaptation, and further development at the cost of lower accuracy and smaller application range. This study highlights the trade-offs between model accessibility and accuracy, emphasizing the need for further research, development and improvement to enhance the accuracy and applicability of human thermoregulation models in wide range of disciplines.

Keywords: human thermoregulation, model comparison, FPCm model, JOS-3 model

Analysis of Thermal Comfort Cooling Mechanisms to Combat Heat Stress in the Construction Industry

Madeline Poley-Bogan (United States Army Research Institute of Environmental Medicine)
Meredith McQuerry (Florida State University)

Abstract

Heat stress and heat-related illnesses (HRIs) pose a substantial threat to construction workers and the construction industry. Several compounding issues contribute to this: the strenuous nature of construction work, oppressive hot/humid environments, and long working hours. With functional clothing design becoming readily available to the average consumer, incorporating thermal comfort apparel technologies like cooling vests, PCMs, cooling minerals, and ventilation features could be a feasible method for reducing HRIs in the construction workplace. Therefore, the purpose of this research was to evaluate the impact of various cooling technology garments based on a construction worker's typical ensemble and metabolic rate using a dynamic sweating thermal manikin in combination with thermoregulatory modeling. Results demonstrated a significant decrease in skin temperature (TSK) and sweat rate (SWA) for both vests with cooling packs and SHIRT2 with ventilated fabric construction.

Keywords: Thermal Manikin, Clothing Biophysics, Thermoregulatory Model, Modeling, Cooling Garments, Thermal Comfort, Heat Stress

Development and Validation of an Induced Hypothermia Thermoregulation Model for Assessing Patient Warming Devices

Meredith McQuerry (ThermaNOLE Comfort Lab, Florida State University)
Steven Bernal-Diaz (Florida State University)
Andre van Grieken (Florida State University)
Josephine Bolaji (ThermaNOLE Comfort Lab, Florida State University)

Abstract

Unintended perioperative hypothermia can lead to serious postoperative complications. Medical warming devices used during surgery help prevent hypothermia. To accurately assess new warming technologies, an advanced thermoregulation model is needed that can simulate induced hypothermia under anesthesia conditions. The goal of this research is to develop a physiological model that can predict core temperature, skin temperature, shivering response, and patient thermal comfort when using medical warming devices. The model will be validated against available clinical data. It will then be used to test and optimize new warming products to improve outcomes for surgical patients vulnerable to unintended hypothermia. The model incorporates key physiological parameters like sweating, shivering, vasoconstriction, and skin blood flow. Testing will use a thermal manikin to evaluate device performance by measuring impacts on temperature regulation under multiple conditions including different vasoconstriction levels. Findings aim to provide evidence-based recommendations to iterate and enhance warming protocols and device design. This research advances thermal technology innovations in medicine while ensuring proprietary information remains confidential. Overall, the project furthers capabilities in induced hypothermia modeling to generically assess patient warming systems and optimize their performance to prevent unintended surgical hypothermia.

Keywords: Thermal manikin, Induced hypothermia, Operating theatre, Thermoregulation, Modeling

A Step Behind: Occupational Safety and Performance Impacts of Inadequate PPE Footwear for Women

Susan Sokolowski (University of Oregon)

Abstract

Research indicates that women are more likely to experience uncomfortable safety footwear than men (Janson, Newman, Dhokia, 2021). Although women have been in occupations like firefighting, law enforcement, and the armed forces for decades, minimal effort has been focused on improving PPE footwear comfort. Many manufacturers attempt to address this problem by creating men's and women's sizes. Unfortunately, too many manufacturers use what is called a "shrink and pink" method, where existing men's footwear models are developed in alternative feminine colorways (e.g. pink) and resized down numerically as the solution for women (Theivam, 2020). This method algebraically is ineffective as women's feet have a shorter heel-to-ball length, narrower ball, instep, heel along with a larger toe region, instep, and medial and lateral malleoli heights (Luo, Houston, Mussman, Garbarini, Beattie & Thongpop, 2009). In addition to sizing and fit, PPE footwear comfort must also consider physiological and biomechanical needs to enable adequate performance. Physiologically, due to hormonal fluctuations, receptor density and surface area women have different footwear flexibility, sensitivity and thermoregulation needs (Hartman, Fehr & Gianakos, 2024; Greenspan, Craft, LeResche, Arendt-Nielsen, Berkley, Fillingim, Gold, Holdcroft, Lautenbacher, Mayer & Mogil, 2007; Burse, 1979). Biomechanically, because women on average weigh less and have a different foot strike, there is a need to engineer sock liner, midsole and outsole shapes/patterns differently (Nigg, Baltich, Maurer & Federolf, 2012, Sinclair, Greenhalgh, Edmundson, Brooks & Hobbs, 2012). Without holistic and accurate consideration of these parameters, PPE manufacturers are putting women at a safety risk. This research will demonstrate considerations in the footwear design process (e.g., form, materials, testing) that can change how PPE footwear is developed for women in the future, ultimately contributing to safer and more inclusive work environments.

Keywords: PPE, Footwear, Women, Safety, Performance

Integrating Strategic Design and 3D Simulation to Enhance ECG Signal Quality and Fit

Kavita Mathur (Wilson College of Textiles, NCSU)
Amanda Mills (Wilson College of Textiles, NCSU)
Seonyoung Youn (Cornell University)

Abstract

Wearable biosignal monitoring systems are emerging as a crucial tool for autonomous health monitoring. However, these systems' design often neglects anthropometric considerations for the female form, resulting in ineffective, ill-fitting devices. This oversight is particularly evident in the suboptimal placement of 3-lead electrodes, inappropriate material selection, and poor fit for women. This study introduces a customized electrocardiogram (ECG) sports bra design, balancing enhanced biosignal quality with wearing comfort. This study focuses on determining the optimal electrode placements under the chest, selecting strategic knit fabrics, and simulating targeted garment pressure using digital twins. The efficacy of the devised ECG sports bras is evaluated against the standard wet-electrode, assessing ECG data quality, signal-to-noise ratio (SNR), and skin-to-electrode impedance. We also explore the aspects of fit and pressure comfort for user experience.

Keywords: Wearables, Biosignal, 3D Simulation, Pressure, Comfort

Lab-based Tribological Assessment of Multi-Fiber Sport Sock Compositions on Sport Performance Footwear Interface Coefficient-of-Friction (COF) Under Load

Kedena Henriques-Thompson (North Carolina State University)
Emiel Denhartog (North Carolina State University)
Pamela McCauley (Widener University)

Abstract

Imbalance of foot gait cycles and interactions between performance footwear with ground surfaces can result in the high number of athlete injuries to their lower body extremities such as ankles, medial and anterior ligaments. However, considerations of the in-shoe friction interactions between the wearers plantar skin surface, sock, and sock-liner-top-cloth (SLTC) as a thermo-physiological initiation of foot slippage for lack of foot stability is open for further exploration. Micro-climate foot friction between wearer sport performance socks and SLTC plays a critical role during sport and occupational activities as friction impacts the full gait mobility of the wearer from heel strike to stance and terminal swing. Low friction has a high slip risk while very high friction can provide a strong foot plantar grip but can limit full and comfortable mobility. Textiles comprising the footwear microclimate are the closest materials to wearers plantar foot surface and are therefore the most important layers in closest proximity to the skin. Using laboratory-based tribological testing methods, the test consists of 6 types of socks with multi-fibers and composition percentages against three sport performance SLTC. I seek to characterize the frictional behavior of performance sock fibers with the objective to provide textile engineering insights into the optimal sock selections for medium coefficient-of-friction (COF), minimizing friction-induced injuries and microclimate foot slippage between socks and SLTC. Friction between socks and SLTC, can be a precursor to slippage, perspiration, and thermal gradation. However, no standardized method seeks to assess the internal interactions. By adapting and expanding testing methods such as ASTM F2913, where the coefficient-of-friction is evaluated between footwear and test surfaces/flooring, this research pursues a more comprehensive approach and understanding of how footwear textiles impact frictional forces and thermos-physiological implications in varying conditions. This research aims to quantify and compare COF between the sport performance socks vs SLTC and to define "optimal/safe" friction levels for footwear microclimate. My key hypothesis proposes the socks composition containing cotton will have the highest COF, and socks with the highest percentage of polyester fibers will have the lowest COF. Future studies will include multi-grade moisture levels to simulate sweat accumulation in the sock and SLTC textiles and the impact ankle and lower limb stability using 3-D foot gait analysis full body motion capture and BIOPAC EMG100C for muscular reflexes analyses.

Keywords: Tribology, Coefficient of Friction (COF), Footwear Microclimate, Skin-Sock Interface, Sock Fiber Composition, Foot Slippage, Thermo-physiological interaction

Characterizing the Tactile Comfort of Contaminated Wildland Firefighters' Personal Protective Clothing

Sumit Mandal (Oklahoma State University, Stillwater, Oklahoma)
Sayak Nandi (Oklahoma State University, Stillwater, Oklahoma)
Md. Momtaz Islam (Oklahoma State University, Stillwater, Oklahoma)

Abstract

In recent years, there has been an increase in the frequency of large, uncontrollable wildland fires. By wearing the same fireproof single-layered fabrics based Personal Protective Clothing (PPC), on-duty wildland firefighters work for 8-16 hours/day for several days. Evidently, wildland firefighters' PPCs get contaminated with high-amount of soot-ashes and this contaminated PPC directly interact with firefighters' skin-sensory-system. Wearing this contaminated PPC significantly affect neurophysiological sensory perceptions and compromise the tactile comfort of firefighters. This paper investigated the impact of contaminated PPC on tactile comfort of wildland firefighters. For this study, we have selected a set of different structures and physical properties based single-layered fabrics i.e., commercially used in wildland firefighters' PPC. Then, we contaminated these fabrics with 0% (non-contaminated), 25%, and 50% soot-ashes mixtures. The tactile comfort properties of these non-contaminated and contaminated fabrics were measured by using the Kawabata Evaluation System (KES). This KES possess a series of 4 instruments to measures the mechanical properties of fabrics that enables to predict the tactile comfort perceived through human/textiles interaction. We measured the mechanical properties such as tensile (stretching), shear (draping), bending (flexing) and surface friction-roughness (prickling) at low forces that is simulating human touch to fabrics. The comparison in mechanical properties between different fabrics and contamination levels are carried out through inferential statistical analysis. It has been found that trapping of soot-ashes in the fabric structure differs the mechanical properties. This phenomenon is also dependent upon the structure and physical properties of the fabrics. Depending upon the level of contaminations, the bending righty and surface roughness of the fabrics significantly get changes, in turn, tactile comfort related to flexibility and prickliness substantially get compromised. This study could lead towards identifying the maximum level of contamination in PPC that can significantly deteriorate the tactile comfort of firefighters and requires immediate washing/decontamination.

Keywords: Protective Clothing, Wildland, Tactile Comfort, Contamination, Safety

Influence of Air Velocity Variations on Manikin Thermal Resistance Measurements Following Standard Test Methods

Meredith Schlabach (Kansas State University)
Danielle Lichtenwalner (Kansas State University)
Steven Eckels (Kansas State University)

Abstract

Thermal manikins are used to measure the thermal resistance (insulation) of clothing ensembles. This data is used by brands to evaluate clothing, personal protective gear, and cold weather clothing, as well as to inform improvements and to provide consumer facing claims. Therefore, it is important for test results to be repeatable and reproducible. Every test result has a measurement uncertainty associated with it. Modern thermal manikins are very sophisticated, and the measurement uncertainty associated with the manikin equipment is relatively low. The two most significant contributions to measurement uncertainty in manikin testing are typically dressing variability and air velocity variability. The purpose of this study was to evaluate the impact of changes in air velocity on the measured thermal resistance value when following standard test methods.

ASTM F1291, Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin, specifies test conditions with an air velocity of 0.4 m/s ± 0.1 m/s. ISO 15831 is a similar standard and has the same air velocity requirement. Data were collected using a child-size thermal manikin in a controlled environmental chamber with a wind tunnel having documented air velocity profiles. Three different air velocities (0.3 m/s, 0.4 m/s, and 0.5 m/s) were selected to correspond to the range of values in the standard test methods. Three different clothing conditions (nude, a standard base ensemble, and a cold weather clothing ensemble) were also used.

Total thermal resistance values were measured, and intrinsic thermal resistance values were calculated. Total thermal resistance values include the thermal resistance provided by the clothing and the surrounding air layer. Intrinsic thermal resistance values are for the clothing only and are obtained by subtracting the air layer thermal resistance (i.e., the nude thermal resistance corrected for surface area) from the total thermal resistance value. Intrinsic values are often used with the understanding that they can account for differences in air velocities for both interlaboratory and interlaboratory testing.

The variation in total thermal resistance values was the greatest for the nude condition, and the least for the most heavily clothed condition. Over the velocity range permitted by the standard test methods, the nude resistance value varied by 7%. For the most heavily clothed condition, the total thermal resistance value varied by 4%. The use of intrinsic values did not completely correct for the differences in air velocities. The variation in intrinsic thermal resistance values was about 3% for both the medium and heavily clothed conditions. This illustrates that results can vary 3% due to changes in air velocity alone, while remaining compliant with the requirements in the standard test methods. It is recommended that efforts to improve standard test methods carefully take into consideration air velocity requirements.

Keywords: thermal manikin, clothing insulation, clothing thermal resistance, ASTM standard, standard test method, measurement variability, measurement uncertainty, air velocity variability

Finite Element Modelling and Deformation Analysis of Compression Stockings

Ingrid Estefany Peraza Melendez (TU Dresden)
Ann-Malin Schmidt (TU Dresden)
Karl Hesse (TU Dresden)
Yordan Kostadinov Kyosev (TU Dresden)

Abstract

Compression stockings are specialized garments designed to apply a controlled gradient pressure along the legs, enhancing venous return and promoting blood circulation. They play an important role in athletic support and recovery, while medical-grade compression stockings help manage chronic venous disorders, reduce swelling, and prevent deep vein thrombosis. Despite their broad application and use, optimizing the design and performance of compression stockings remains challenging due to their complex hyperelastic behavior and frequent issues with improper fit or prescription.

In this context, Finite element modeling (FEM) provides a robust approach and a powerful tool for simulating garment-body interactions, and analyzing compression distribution, enabling insights that extends beyond what can be achieved through experimental methods alone. Meanwhile, 4D scanning techniques enables the capture of precise body deformations during motion and fit variations, allowing to evaluate garment performance under dynamic conditions.

This study builds upon and adapts the methodology proposed by Schmidt (2025) to analyze the mechanical and comfort performance of compression stockings using advanced 4D scanning techniques to capture detailed human body geometries, and Finite Element Modelling (FEM) to model the interaction between the deformable leg tissues and the stockings, considering both their elastic and compressive behavior. The approach involves both static FE simulations of compression forces and dynamic assessments from the Scanning technology under different movement scenarios.

Keywords: Compression stockings, 4D Scanning, Finite Element Modelling, Garment-tissue interaction

Opportunities and Challenges for Digital Image Correlation Analysis of Surface Strain to Inform Wearable Product Design: A Case Study of the Finger and Glove

Olaitan Adeleke (University of Minnesota)
Alireza Golgouneh (University of Minnesota)
Eric Beaudette (University of Minnesota)
Bolanle Dahunsi (Oregon State University)
Heidi Woelfle (University of Minnesota)
Brad Holschuh (University of Minnesota)
Lucy Dunne (University of Minnesota)

Abstract

Digital Image Correlation (DIC) is an optical method of mapping strain in surfaces that measures the movement of pixels in successive images of a surface pattern to derive the forces acting on the surface. While well-established in other fields (particularly for stiff materials), it has only rarely been explored as a tool for understanding deformations of the body or worn garments. A key challenge is that commercial DIC systems are not optimized for capturing 3D bodies or garment surfaces, and can struggle to capture and measure 360° views, occlusions, and wrinkles. Strain is a key indicator of comfort and wearability and is also vital for force-related wearable technology applications, like sensing skin or garment strain or for supplying active compression. Here, we investigate and evaluate the opportunities and challenges for Digital Image Correlation (DIC) assessment of strain in skin and garment surfaces. Using a case study of the index finger, we investigate system setup and capture parameters, test setup configurations, and metrics and visualizations for collected data. We identify confounding factors that interfere with data collection and accuracy, as well as areas where existing analysis tools are limited in their ability to supply strain analysis metrics useful for movement analysis and device design. These approaches are then applied to an example wearable technology application, where a rigid component is integrated into a stretchable glove on the lateral finger surface, and its effects on strain propagation in the garment are measured and visualized.

Keywords: Strain mapping, Digital image correlation, Finger strain analysis, Clothing modeling

Performance of a Thermode with an Integrated Pressure Sensing for use in Human Cutaneous Temperature Sensitivity Assessments

Inderpreet Bains (Lab for Exercise & Environ Physiol, Dept of Biomedical Physiol & Kinesiol, Simon Fraser University)
Jingkai Pang (Lab for Exercise & Environ Physiol, Dept of Biomedical Physiol & Kinesiol, Simon Fraser University)
Dora Wc Hsiao (Lab for Exercise & Environ Physiol, Dept of Biomedical Physiol & Kinesiol, Simon Fraser University)
Clara V Etter (Lab for Exercise & Environ Physiol, Dept of Biomedical Physiol & Kinesiol, Simon Fraser University)
Paul H-J Cho (Lab for Exercise & Environ Physiol, Dept of Biomedical Physiol & Kinesiol, Simon Fraser University)
Matthew D White (Lab for Exercise & Environ Physiol, Dept of Biomedical Physiol & Kinesiol, Simon Fraser University)

Cutaneous sensory thresholds (CST) are assessed by topical application of a thermode probe on different body surfaces. Variations in the surface application pressure of thermodes for CST determinations is a source of variability for these thresholds. This led us to develop a thermode probe with integrated pressure sensing to allow for the control of surface application pressure during CST testing.

Purpose. Develop a reliable thermode probe with the ability to reproducibly control application pressures for use in cutaneous temperature sensitivity testing in humans. METHODS: Two force sensing resistors were mounted on a thermode probe. Known forces of 1.47, 1.96, 2.94, 3.92, and 4.90 N were used in two to five trials to evaluate the force sensing capabilities of the sensor.

Analysis. Bland-Altman plots and intraclass correlation coefficients were employed to test for reproducibility and reliability between applied forces and each of resistance and conductance from the force sensing resistors.

Results. Intraclass correlation coefficients were high and significant ($0.93 < r < 0.98$, $p<0.05$) among 5 trials in resistance and conductance at 1.96 N. Bland-Altman analysis of 2-trial differences of conductance and resistance was not significantly different than zero and when plotted against 2-trial means values that were randomly distributed and within ± 2 standard deviations.

Conclusion. A novel thermode probe with integrated force sensing resistors was conceived, designed, constructed assessed to show reliable and consistent trial-to-trial contact pressures for use in cutaneous temperature sensitivity testing.

Keywords: cutaneous, surface pressure, temperature regulation, thermosensitivity

13th International Manikin & Modelling Meeting (I3M) and The Clothing and Textile Sciences Research Meeting (CTSRM) – Short Papers

October 15-16, 2025

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Park Alumni Center

Quantifying Turbulent Convective Heat Transfer Using an Outdoor Thermal Manikin

Ankit Joshi, Shri H. Viswanathan, Cibin T. Jose, Gokul Pathikonda, and Konrad Rykaczewski
School for Engineering of Matter, Transport and Energy, Arizona State University

Accurately characterizing convective heat exchange between the human body and its environment is important for assessing thermal stress and comfort under a variety of conditions. Traditional convective heat transfer correlations, developed primarily from indoor studies, often fail to accurately represent complex outdoor environments characterized by transient airflow and turbulence. To address this gap, we employed a novel outdoor thermal manikin ("ANDI") equipped with 35-zone temperature and heat flux sensors, along with a three-level ultrasonic anemometer array and Integral Radiation Measurements (IRM), to quantify convective heat flux in diverse outdoor scenarios [1].

Field experiments were conducted over 20 days in shaded outdoor settings with air temperatures up to 45°C, wind speeds ranging from 0.7 to 4.5 $m \cdot s^{-1}$, turbulence intensities as high as 46%, and turbulence length scales between 0.5 and 15 m. Results indicated a robust correlation between local convective heat transfer coefficients and wind speeds, emphasizing that turbulence intensity and length scale significantly influence convective heat transfer. By fitting our measured data to the established Kondjoyan-Daudin-Sak correlation for turbulent cross-flow, we determined universal, geometry-based parameters, resolving existing discrepancies among traditional correlations.

The outcome is a geometry-informed correlation that accurately predicts convective heat transfer across diverse body segments, sizes, and environmental conditions, suitable for both indoor and outdoor settings. The improved predictive accuracy can inform urban design, outdoor activity guidelines, and protective clothing strategies, enhancing human adaptation to increasingly severe heat exposure.

[1] Joshi et al., Sci. Total Env., 2024.

Performance of a thermode with an integrated pressure sensing for use in human cutaneous temperature sensitivity assessments

Inderpreet K Bains[1], Jingkai Pang[1], Dora W.C. Hsiao[1], Clara V. Etter[1], Paul H-J Cho[1] and Matthew D. White[1]

[1]Laboratory for Exercise and Environmental Physiology,

Department of Biomedical Physiology and Kinesiology,

Simon Fraser University,

Burnaby, British Columbia, CANADA, V5A 1S6.

Address for correspondence:
Dr. Matthew D. White,
Laboratory for Exercise and Environmental Physiology,
8888 University Drive, School
of Kinesiology,
Simon Fraser University,
Burnaby, British Columbia, CANADA, V5A 1S6.

Email: matt@sfu.ca
Tel no.: +1-778-782-3344
Fax no: +1-778-782–3040

Abstract

Cutaneous sensory thresholds (CST) are assessed by topical application of a thermode probe on different body surfaces. Variations in the surface application pressure of thermodes for CST determinations is a source of variability for these thresholds. This led us to develop a thermode probe with integrated pressure sensing to allow for the control of surface application pressure during CST testing. **PURPOSE:** Develop a reliable thermode probe with the ability to reproducibly control application pressures for use in cutaneous temperature sensitivity testing in humans. **METHODS:** Two force sensing resistors were mounted on a thermode probe. Known forces of 1.47, 1.96, 2.94, 3.92, and 4.90 N were used in two to five trials to evaluate the force sensing capabilities of the sensor. **ANALYSIS:** Bland-Altman plots and intraclass correlation coefficients were employed to test for reproducibility and reliability between applied forces and

each of resistance and conductance from the force sensing resistors. **RESULTS:** Intraclass correlation coefficients were high and significant ($0.93 < r < 0.98$, $p<0.05$) among 5 trials in resistance and conductance at 1.96 N. Bland-Altman analysis of 2-trial differences of conductance and resistance was not significantly different than zero and when plotted against 2trial means values that were randomly distributed and within ± 2 standard deviations.
CONCLUSION: A novel thermode probe with integrated force sensing resistors was conceived, designed, constructed assessed to show reliable and consistent trial-to-trial contact pressures for use in cutaneous temperature sensitivity testing.

Keywords: cutaneous, surface pressure, temperature regulation, thermosensitivity

Introduction

Cutaneous sensory thresholds (CST) are widely used (5) in numerous research fields as part of the thermosensory evaluations of human thermal perception (3). This includes both in research and development for thermal comfort of technical apparel and in clinical settings as an assessment metric for sensory dysfunctions and neurological disorders (1, 9). The accuracy of CST assessments assessed with thermode probes are influenced by various external variables. These include body surface application pressure of the probe, the anatomical location of the probe's application, ambient temperature and magnitude of the probe's thermal stimuli (7, 8, 15). Amongst 21 studies, Molony et al. reported considerable variability in the reliability of thermal quantitative sensory testing parameters (13) and identified studies showing concomitant pressure (14, 17, 18) and variable stimulus pressure can affect thermal sensation during thermal sensitivity testing (7). This supports that variable body surface application pressure of the thermode probe may lead to inconsistent results when determining CST (10).

The physiological rationale for assessing thermode application pressure during cutaneous temperature sensitivity assessments is that both thermal and pressure stimuli can activate transient receptor potential and piezo-type mechanosensitive membrane ion channels. As these channels participate in the initiation of the signals coding for temperature that are sent to the thalamus and cerebral cortex for thermal perception (11), it appears warranted to control for their activation by pressure. Despite this, few studies have considered the effects of the application pressure of thermodes during cutaneous temperature sensitivity assessments (12, 15).

Consequently, a thermode probe system was developed with the ability to change temperature of its contact surface with control of its application pressure. We report here on the reliability and reproducibility of body surface application pressures of this novel thermode probe system with integrated pressure sensing capability.

Methods

Instrumentation: Pressure application of this novel thermode probe was by two round-head Force Sensing Resistors (FSR® 400, Interlink Electronics, Camarillo, CA, USA), each with a force sensing surface area of ~ 0.08 cm^2 (Fig. 1). These FSR were placed between two 15.82 cm^2 plexiglass rings on a plastic collar shaft (Zoro, Inc, Buffalo Grove, IL, USA) attached to a thermode probe (NTE-2A, Physitemp Instruments Inc., Clifton, NJ, USA). Outputs of the FSR were collected with a data acquisition system (SCXI-1000, Austin, TX, USA) controlled by LabVIEW software (Ver. 7.1, National Instruments, Austin, TX, USA) on a personal computer.

Five different calibration weights of 150, 200, 300, 400, and 500 g (OHAUS Corporation, Parsippany, NJ, USA) were placed on the contact surface of the novel pressure sensing thermode system giving forces of 1.47, 1.96, 2.94, 3.92, and 4.90 N. Weights were evaluated for accuracy using a digital LCD balance with a precision of ± 0.1 g (Acculab, VI-1200, London, ON, Canada).

Protocol: One of the five calibration weights was chosen at random and placed on the contact surface of the thermode probe with integrated pressure sensing for 120 s. This process was repeated for each of the five calibration weights, with a 30 s break between trials. Each calibration weight was assessed twice except for the 200 g calibration weight which was assessed five times.

Analyses: Reproducibility and reliability of resistance or conductance outputs between the two trials for all five calibration weights was analyzed with Bland-Altman plots (2). Intraclass correlation coefficient (ICC) analysis was used to determine the similarity between FSR outputs over 2 trials for all forces and for 1.96 N over five trials. Fleiss (4) indicated an ICC >0.75 represents excellent reliability and this value was used to assess reproducibility between trials. Linear regression analysis was employed to assess the relationship between force (F, N) and both resistance (R, Ohms, W) and conductance (G, Siemens, S). The alpha level was set at 5%.

Results:

Linear regression analysis of force (F, N) plotted against the mean resistance (R, W) over five trials for 120 s showed an $r^2 = 0.99$ (n=5). This gave linear regression equation of F = -0.0009*R + 29.5 (Fig. 2). Linear regression analysis of force versus conductance (G, S) over five trials for 120 s showed a $r^2 = 0.99$ (n=5) with a linear regression equation of F = 804912 * G - 23.1 (Fig. 3).

Bland-Altman assessments for mean resistance over 120 s of force application to the novel thermode probe system (Fig. 4) displayed mean between trial resistances within the ± 2 SD limit of 374 Ω. From the linear regression analysis mean 2-trial differences were randomly distributed about zero with an $r^2 = 0.26$ ($p>0.05$). The mean 2-trial difference for resistance was not significantly different from zero (p = 0.53, n=5). The Bland-Altman assessment for conductance (Fig. 5) gave mean between trial values within the ± 2 SD limit of $3.83 \times 10^{-0.7}$ S.

The linear regression analysis values were randomly distributed about zero $r^2 = 0.27$ ($p>0.05$). The mean 2-trial difference for conductance was not significantly different than zero (p = 0.46, n=5).

Intraclass correlation analysis of the resistance for 2 trials (n=5) gave an ICC = 0.98. Intraclass correlation for the 5 trials for resistance at 1.96 N gave ICC= 0.93.

Discussion:

A novel thermode probe system that permits control of its' application pressure was conceived, designed and constructed for cutaneous temperature sensitivity testing in humans (Fig. 1). For this thermode probe system with integrated pressure sensing, Bland-Altman plots (Fig. 4 and 5) revealed no significant bias or trends between two trials for either resistance or conductance. For both resistance and conductance, the differences between two trials plotted against the 2-trial means were randomly distributed and they were not significantly different than zero. In addition, the ICC from the analysis were high and significant showing good reproducibility of the application pressures of the novel thermode probe system. Collectively the findings support the reliability and reproducibility of application pressure using this novel thermode probe system.

Further development and use of this system stands to help address an important concern on the accuracy of thermosensory evaluations for human thermal perception (3). This is in settings such as that for the thermal comfort evaluations during R&D of technical apparel or during diagnoses of sensory dysfunction and neurological disorders in clinical settings (1, 9). This novel system stands to enable more consistent cutaneous temperature sensitivity testing across different body surfaces and is targeted to improve assessments of human thermal perceptions.

The literature indicates various factors can influence human cutaneous thermosensitivity assessments (8, 15). These factors include, but are not limited to, thermode probes with differing size and material composition influencing their heat flux rates (15), thermosensitivity tests with differing rates of temperature change (6, 16), as well as varied thermode probe application forces on the skin surface (12). A previous study developed a thermode to address the last concern of application force of thermode probes when assessing human cutaneous thermosensitivity (15); the outcomes of their novel device and study had some potential limitations. From the different composition material of their pressure sensor relative to that of their thermode (15) it appears this would have given a change in heat flux to and from the skin and an assessment of reproducibility among trials in the study would have strengthened this outcome. With a goal to contribute and help strength assessment methods of human cutaneous thermosensitivity, the current novel thermode probe system was assessed for its reliability and reproducibility prior to its employment in human testing.

It is intended to make improvements to the current novel thermode probe system. Tissue compressibility varies on differing arm or other body surface areas. An approach to attenuate these potential differences is to standardize the body surface location of thermal threshold testing. Future efforts, however, can also be targeted to assess differences in the thermal perception on body surfaces that differ in tissue compressibility. Establishing what surface application pressure(s) of the thermode are optimal to simulate garment-skin interface pressures on different body surfaces also stands to help improve the validity of human thermal perception assessments during the R&D of technical apparel. In clinical settings employing varied application pressures of this novel thermode probe system has potential to contribute to a better understanding of the mechanisms underlying sensory dysfunction and neurological disorders.

Conclusion:

A novel thermode probe system with integrated pressure sensing was conceived, designed, constructed and assessed for use during cutaneous temperature sensitivity testing in humans. The probe's application pressure demonstrated excellent reliability and reproducibility across repeated trials, supporting its future use in thermal perception testing in R&D of technical apparel and in clinical settings.

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Figure 1: Schematic diagram of the integrated pressure sensing thermode probe.

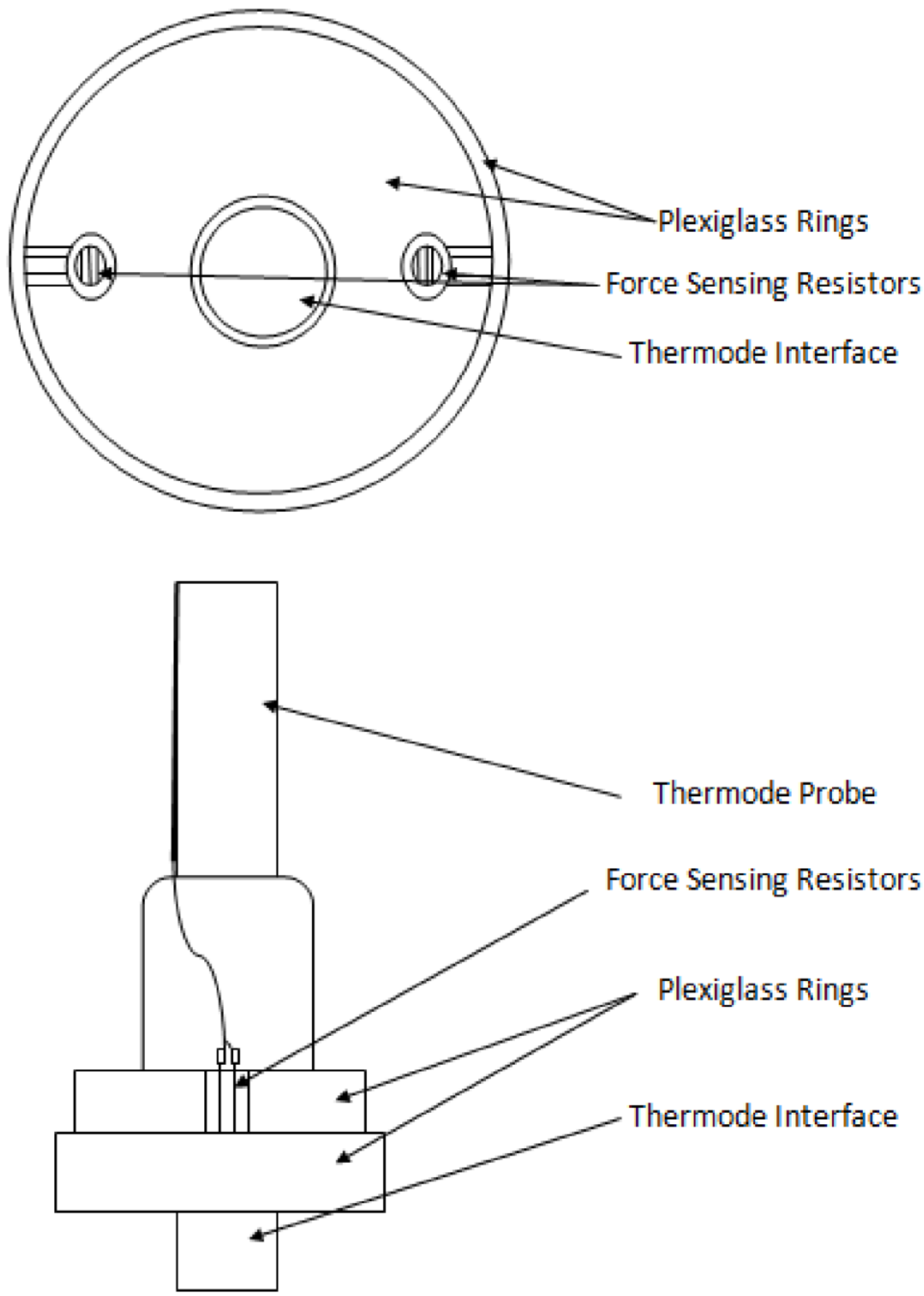


Figure 2: Linear regression analysis of force as a function of resistance. Values in the plot are means during steady states within the 120 s of the application of the probe.

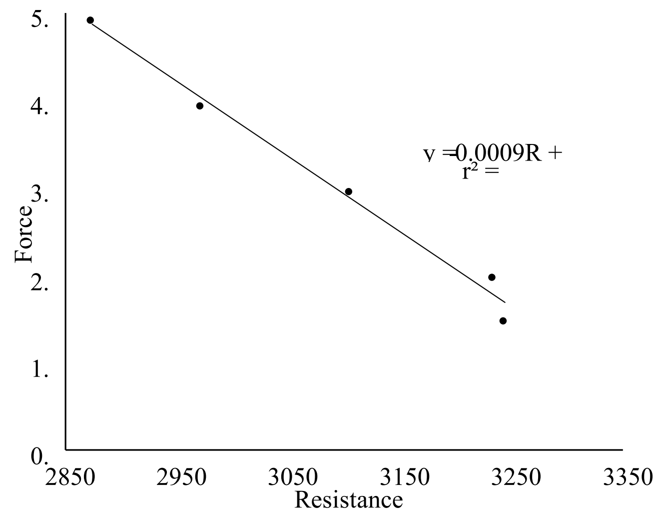


Figure 3: Linear regression analysis of force as function of conductance. Values in the plot are means during steady states within the 120 s of the application of the probe.

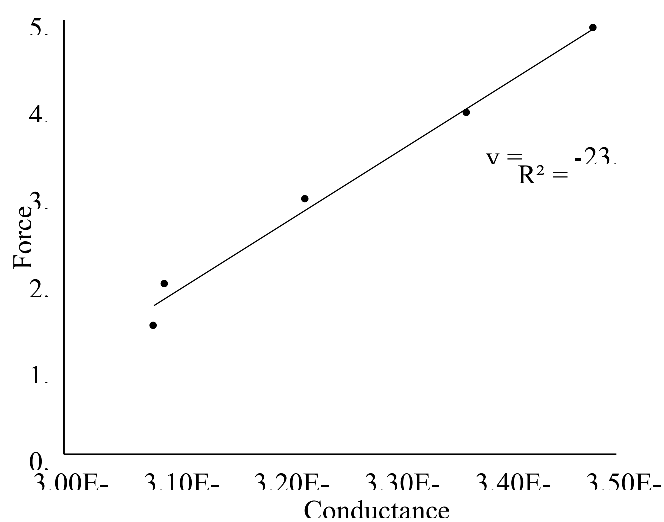


Figure 4: Bland-Altman plot for difference between trial 1 and trial 2 resistance vs. mean resistance (R) of both trials. Horizontal dashed line give ± 2 standard deviations.

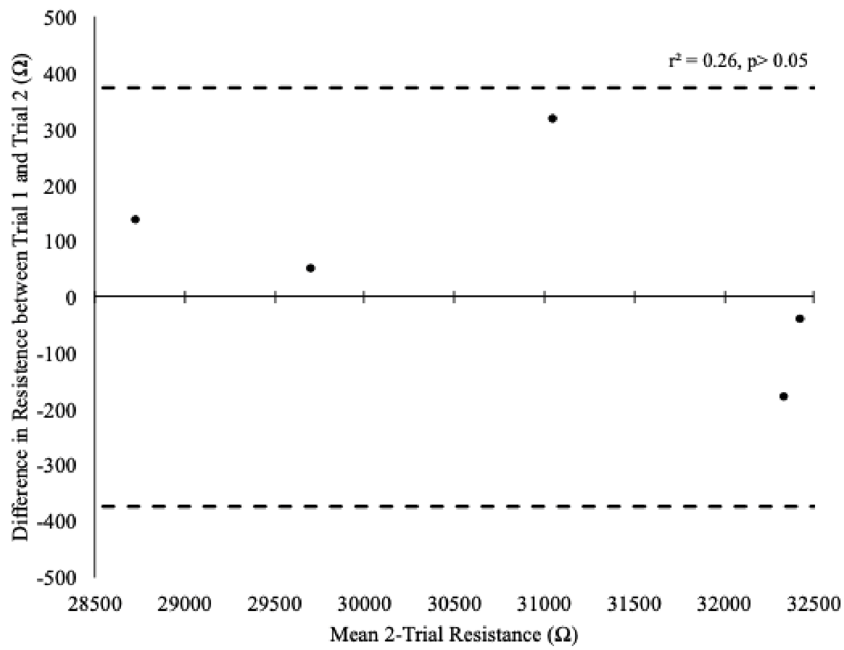
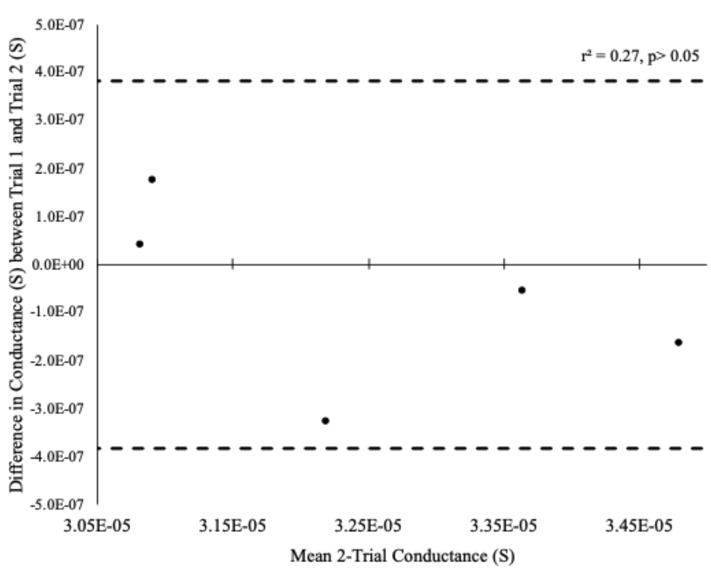


Figure 5: Bland-Altman plot for difference between trial 1 and trial 2 conductance vs. mean conductance of both trials. Horizontal dashed line give ± 2 standard deviations.



Finite Element Modelling and Deformation analysis of Compression stockings

Peraza, Ingrid[1], Kyosev, Yordan[1], Tal, Ann-Malin[1], and Hesse, Karl[1]
[1] Chair of Development and Assembly of Textile Products, ITM, TU Dresden, Germany
Corresponding author: ingrid.peraza@tu-dresden.de

Abstract. Compression stockings are specialized garments designed to apply a controlled gradient pressure along the legs, enhancing venous return and promoting blood circulation. They play an important role in athletic support and recovery, while medical-grade compression stockings help manage chronic venous disorders, reduce swelling, and prevent deep vein thrombosis. Despite their broad application and use, optimizing the design and performance of compression stockings remains challenging due to their complex hyperelastic behavior and frequent issues with improper fit or prescription. In this context, Finite element modeling (FEM) provides a robust approach and a powerful tool for simulating garmentbody interactions, and analyzing compression distribution, enabling insights that extends beyond what can be achieved through experimental methods alone. Meanwhile, 4D scanning techniques enables the capture of precise body deformations during motion and fit variations, allowing to evaluate garment performance under dynamic conditions.
This study builds upon and adapts the methodology proposed by to analyze the mechanical and comfort performance of compression stockings using advanced 4D scanning techniques to capture detailed human body geometries, and Finite Element Modelling (FEM) to model the interaction between the deformable leg tissues and the stockings, considering both their elastic and compressive behavior.

Keywords: Compression stockings · 4D Scanning · Finite Element Modelling · Garment-tissue interaction.

1. Introduction

Compression stockings (CS) play a key role in medical and therapeutic applications by enhancing blood circulation and promoting venous return [1]. They are widely used to manage swelling, varicose veins, chronic venous disorders, deep vein thrombosis, and pregnancy-related edema [2], [3], and have also shown benefits in athletic performance and recovery [4]–[6]. Despite their broad application, optimizing CS design remains challenging due to the complex physiological interaction between the garment and the leg.

Finite element modeling (FEM) offers a powerful framework for simulating these interactions, enabling detailed analysis of mechanical behavior and pressure distribution beyond the limits of experimental testing [7], [8]. This approach is critical for improving CS functionality [9], [10], but key challenges persist, particularly in generating realistic geometries, calibrating material properties, and defining robust validation methods.

A central limitation in current FEM studies lies in the oversimplified modeling of both leg and garment geometries. Leg models are often surface meshes from 3D scans [11] or solids from MRI/CT data that omit internal structures like bones [12]–[14], while stockings are typically approximated as cone-like shells based on external dimensions [11], [14], [15]. This simplification reflects a tradeoff between computational cost and anatomical accuracy.

To address these gaps, this study proposes an innovative method for constructing the geometry of the leg and compression sock, using 4D scan technology and integrating a simplified skeleton. In addition, 3D fashion design software is used to construct a more realistic 3D model of the compression stocking. Experimental tests are performed to validate both leg and stocking geometries, while a method is proposed to validate the leg models through experimental measurements of tissue stiffness. The goal is to achieve an optimal balance between computational efficiency and anatomical accuracy, ultimately constructing a model that integrates and dresses the compression sock over the leg.

1. Methodology

Figure 1 summarizes the workflow used to close the identified gap: (1) construction of a subject-specific leg model; (2) creation of the compression-stocking geometry with CLO3D; (3 & 4) experimental validation of both components; and (4) integration of both models in LS-DYNA to simulate stocking–leg interaction and quantify the resulting pressure distribution.

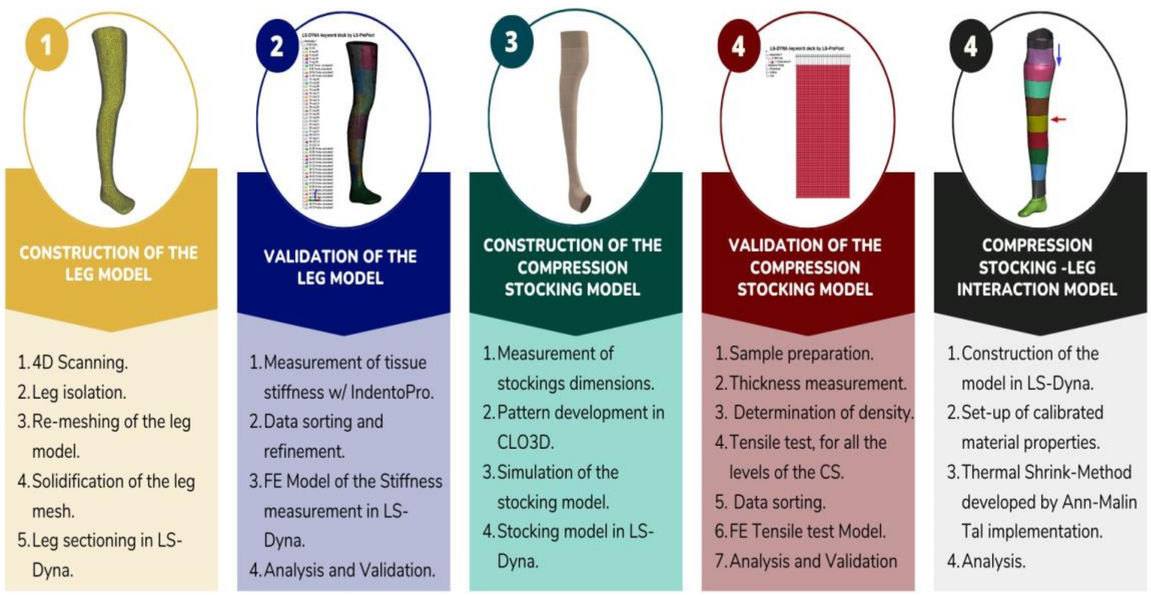


Fig.1: Methodology: General steps to build and validate the Leg-Stocking FE Model.

2.1 Leg Model Construction

A healthy 25 years old female subject, 160 cm height, and weight of 52 kg was scanned in an standard A-pose, using the dynamic body 4D scanner Move4D Scanner developed by IBV (Fig. 2a).

(a) (b)

Fig.2: a) Subject scanned in A-pose, b)Isolated and remeshed leg model

From the scan the leg was isolated up to the thighs, approximately at crotch height using Blender, and vertically aligned, the toes were removed to prevent potential collisions during FE model simulations. Subsequent modifications included sealing any resultant holes and refining the mesh using the Isotropic remesh function set to a 3D resolution of 5 mm available in ArtecStudio Software. This process resulted in a mesh resolution of 14,887 vertices and 29,770 faces (Fig. 2b).

2.2 Validation of the Leg Model

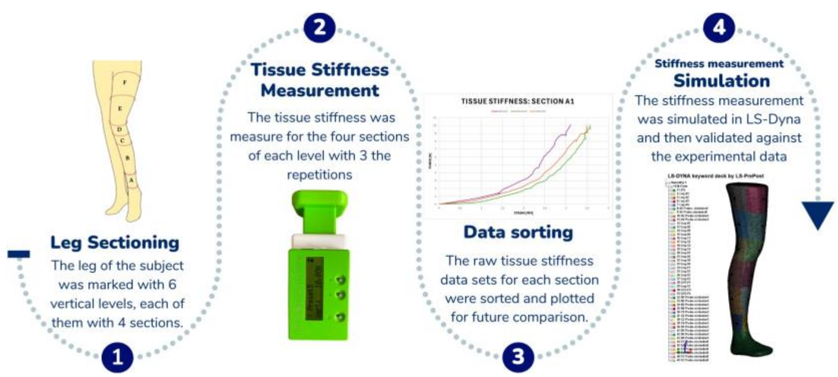


Fig.3: Methodology: Validation of the Leg model.

In order to calibrate material properties through a Finite Element Model, experimental measurements of soft tissue stiffness were performed in the subject, using with the method developed by Schmidt [16]. This experiment was then replicated in finite element simulation where the values of force and strain from the model where compared against the experimental ones (Figure 3).

The leg of the subject was divided into six areas from A to F, based on a typical Compression sock sizing chart, as shown in Fig.1-step 1. Each of these areas was further subdivided into four sections: the front (A1, B1, C1, D1, E1, F1), the right side (A2, B2, C2, D2, E2, F2), the back (A3, B3, C3, D3, E3, F3), and the left side (A4, B4, C4, D4, E4, F4). The tissue stiffness was measured in triplicate for each section using the digital and portable indentometer IndentoPro (Fig. 4a).

(a) (b)

Fig.4: a) Tissue stillness measurement, b) FE Model of the Indentation test.

The device generated force-strain (or force-displacement) curves capturing the soft tissue's nonlinear response. The datasets (3 repetitions) for the 24 leg sections were plotted for later comparison and validation against the simulation results.

To replicate and calibrate the indentation tests, a finite element (FE) simulation was developed in LS-DYNA. The model included 24 circular rigid shells, each representing the indentation probe with a diameter of 11.3 mm, assigned properties representative of polycarbonate (density = 1×10^{-9} ton/mm^3 , Young's modulus = 2×10^5 MPa, Poisson's ratio = 0.30), and using Belytschko-Tsay shell elements. These probes were positioned and aligned manually in front of each predefined leg section (Fig. 4b). The leg was modeled using a solid Element formulation ELFORM = 10 and MAT_ELASTIC, with varying thicknesses assigned to each level to reflect anatomical differences in soft tissue. Internally, a rigid bone-like region with fixed constraints and material properties (density = 1.0×10^{-9} ton/mm^3, Young's modulus = 2000 MPa, Poisson's ratio = 0.30) was defined to simulate structural resistance. A displacement–time curve was applied to each probe's central node to simulate the indentation motion, allowing force–strain responses to be recorded and compared against experimental data for model calibration.

2.3 Construction of the Compression stocking model

While the current research uses CAD Software to generate a 3D geometry of the compression stockings, this study proposes the creation of the compression sock model using a 3D fashion design software. The following scheme (Fig. 5) illustrates the steps followed:

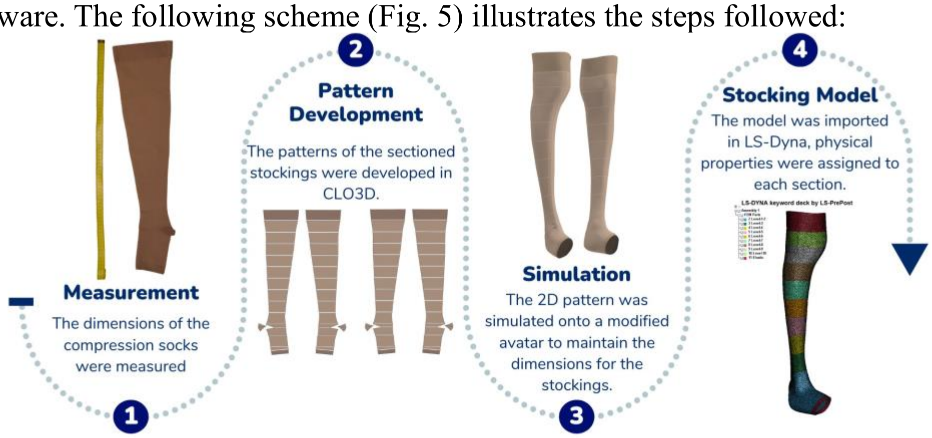


Fig.5: Methodology: Construction of the Stockings model

A compression stockings of Compression class 2 and size II, with composition: Cotton 31%, polyamide 48%, elastane 21% was used to construct the Compression Stocking model. The patterns of the stockings were developed in CLO3D. The patterns were traced over a real photograph of the stockings to accurately capture the contours of the sock and then adjusted to their actual dimensions. The top elastic band, bottom band, and heel were separated from the rest of the sock. Next, the stocking was sectioned into the same regions used in the tensile tests: 5 cm-high sections laid out along the length of the sock and aligned in position and height with the standard rectangular samples extracted for validation (Section 2.4). Finally, these sections were cut and sewn.

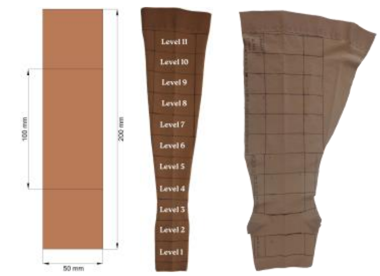
Specific materials were then applied using CLO3D's fabric library: Cotton Stretch Sateen for the Lastofa cotton stockings, Nylon Featherweight for the Memory stockings, and Knitted Elastic for the top, bottom, and heel bands. The patterns were carefully arranged around the modified avatar using pins and the Freeze function to secure positioning. The final output consisted of realistic 3D models of the stockings, which were then exported as mesh objects for further analysis (Fig. 5-step 3).

2.4 Validation of the Compression Sock

To validate the FE model of the compression stocking, physical samples were tested experimentally. Figure 6 illustrates the workflow used to characterize the stocking material, to then replicate its mechanical behavior under tension in a Finite element Simulation. The obtained physical parameters were then used as input for the simulation and to validate its results.

Fig.6: Methodology: Validation of the Stockings model.

The stocking was first marked according to ISO 13934-1 to define standardized tensile test specimens measuring 50 mm × 200 mm, with a 100 mm central gauge length between two 50 mm gripping areas (see Fig. 7a). The marked stocking was then cut along its length to allow direct measurement of thickness at each level, followed by segmentation into 10 individual levels along the leg height (see Fig. 7b). For each level, the fabric's thickness was measured using the Silvac 229 Thickness Gauge, and its density was determined from mass and area measurements. These physical properties served as input for the FE model and helped ensure an accurate representation of the fabric's material behavior.



(a) (b) (c)

Fig.7: a) Standard sample size b) Marked Lastofa cotton, c) Cut stocking for thickness measurement.

Tensile tests were performed using a ZwickiLine universal testing machine, following ISO 13934-1, at a constant speed of 100 mm/min with five loading and five unloading cycles per sample. Force–displacement data was recorded and processed, isolating steady-state cycles for comparison with the simulation. A simplified shell-based FE model was created to replicate the tensile test setup (see Fig. 8), using the measured thickness and density, and assuming linear elastic behavior with properties from literature. A displacement curve of 0.5 mm/s was prescribed, and the simulation outputs were validated against the experimental curves to confirm the model’s accuracy.

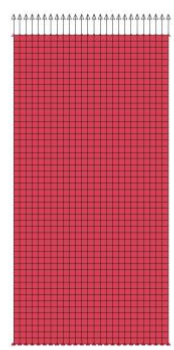


Fig.8: Tensile test FE Model

2.5 Interaction Compression Stocking - Leg Model

The stocking was put on using the thermal shrinking method developed by Schmidt [16].

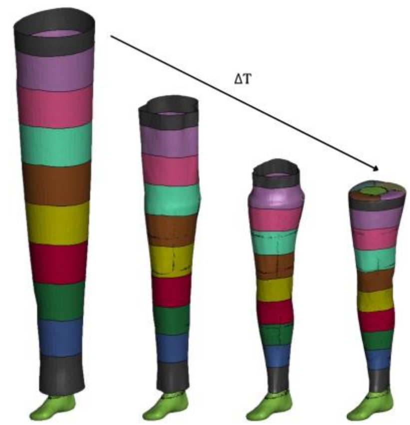


Fig.9: Implementation of the thermal shrink method developed by [16]

3 Results

Finite Element Indentation Model Validation: Leg model

The leg model validation is here exemplified with section B3, located at the back of the leg, characterized by a thicker skin. Figure 10 illustrates the resulting behaviour of the indentation probe in B3, making contact and pressure on the corresponding section.

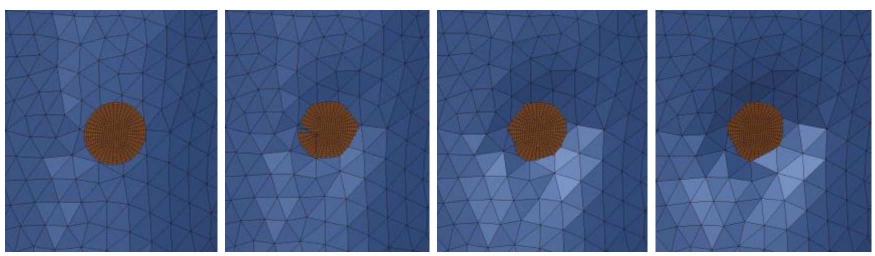


Fig.10: Tissue stiffness measurement in the FE Model: Section B3

The curve Force-Strain obtained for section B3 (Fig. 11) shows that the FE model provided a good fit, especially up to 4 mm of strain. After this point, it exhibits a linear-like increase, indicating again a slight stiffer response compared to the experimental data. However, these are considered negligible, as no high indentation is be expected in this area. The other areas of the leg were calibrated in the same way.

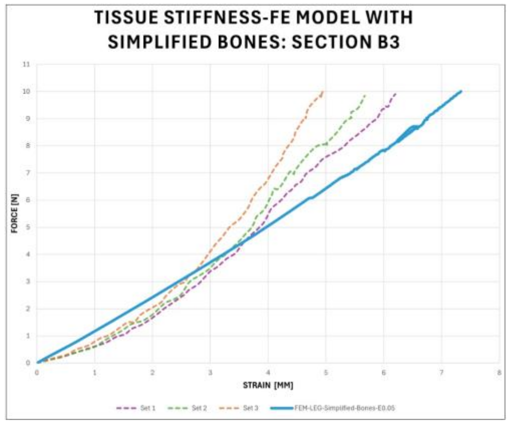


Fig.11: Section B3: Tissue stiffness Finite Element Model vs Experimental results.

FE Indentation Model Validation: Compression stocking

The execution of the Finite Element Model for the Tensile Test showing the progressive vertical displacement of the upper end of the specimen, effectively simulating the elongation observed during the tensile test (Fig. 12).

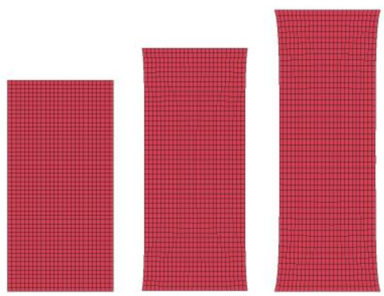
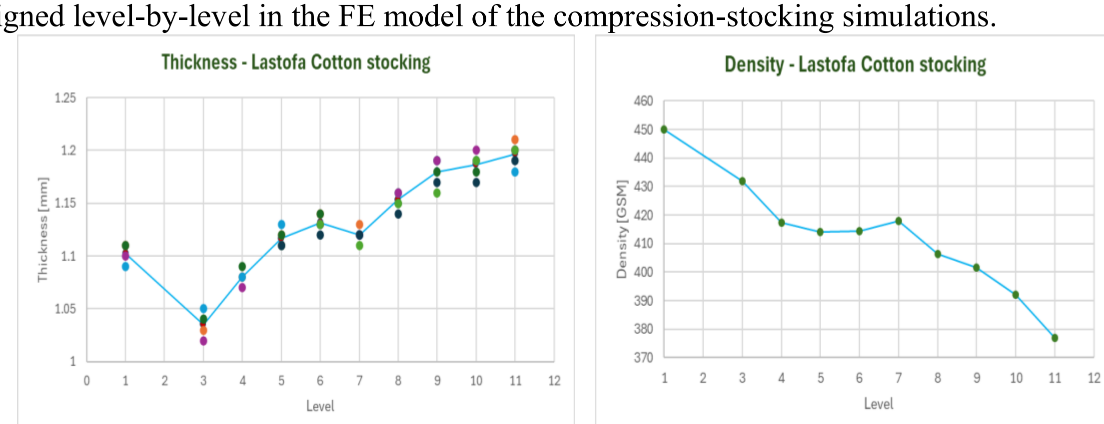


Fig.12: Tensile test Simulation

For the stocking model validation, the experimental tensile test results for the Lastofa Cotton stocking showed a nonlinear force-elongation behavior (blue curve in Fig. 13). As an example, for level 9, the finite element model, (purple curve in Fig. 13) captured very well the stiffness behaviour and accurately reproduce the nonlinearity, providing a reasonable approximation of overall material behavior. After material calibration, the elasticity module was set to 425 kPa for level 9.

Fig.13: Tissue stiffness Finite Element Model vs Experimental results: Section A1

The experimental outcomes for thickness and density are summarized in Figure 14. Both properties vary with along the stocking's height: thickness shows a gradual increase toward the upper levels, whereas density generally decreases from ankle to thigh. These spatially varying measurements capture the material heterogeneity of the Lastofa Cotton stocking. Properties were assigned level-by-level in the FE model of the compression-stocking simulations.

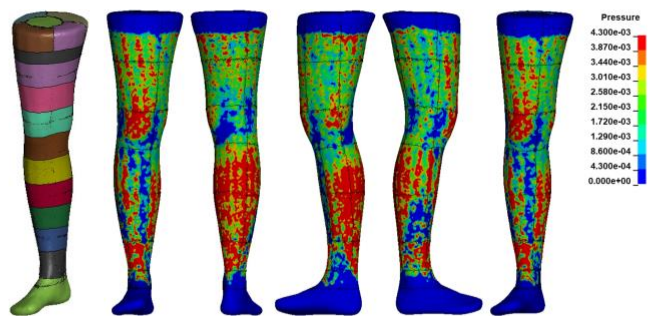


(a) (b)

Fig.14: a) Thickness measurements across all levels, b) Density values across all levels

Model: Interaction Compression Stocking-Leg

Figure 15 illustrates the pressure distribution exerted by the compression stocking on the deformable leg, shown from multiple perspectives. The simulation confirms that the stocking closely follows the leg geometry, indicating a good fit achieved through the proposed method and pattern development (Fig. 15a). The pressure contour map reveals a higher compression at the ankle and lower leg (represented in red and orange), progressively decreasing toward the thigh region (green to blue). This distribution aligns with the intended design of medical grade stockings, which follow a pressure gradient to support venous return. The pressure scale was set to a maximum of 0.0043 MPa, corresponding to the upper threshold of Compression Class II. Localized peaks are visible around the front of the ankle, where bony prominences create concentrated contact areas. Similarly, higher values on the calf compared to the shin reflect the effects of surface curvature. Overall, the simulation results support the physiological plausibility of the interaction between the compression stocking and the leg (Fig. 15b).



(a) (b)

Fig.15: Results of the Interaction-Leg-stocking model

4 Conclusion and Discussion

This study presents a novel integrated workflow for simulating the interaction between compression stockings and the human leg using Finite Element Modelling (FEM). By combining 4D scanning data, fashion CAD modeling, and experimental validation techniques, the method achieves a balance between anatomical accuracy and computational efficiency. Unlike previous works relying on oversimplified geometries, this approach incorporates subject-specific leg models with internal skeletal structure and detailed stocking patterns developed in CLO3D. The proposed methodology for constructing the sock model using dedicated 3D fashion design software enables a more accurate representation of the sock’s shape, including details like heel, open toe, and seams. This approach also facilitates meshing, material property assignment, and separation of the sock into different regions based on varying properties, given the seams of the sock are also part of the mesh. The validation examples of the simplified leg model highlighted the importance of incorporating realistic elements, such as bone, into the leg model, to successfully replicate the natural nonlinear behaviors observed in the leg.

The leg model was validated through indentation tests using the IndentoPro device and replicated in LS-DYNA to capture tissue stiffness in different anatomical regions. Similarly, the stocking material was characterized through tensile tests, and its mechanical response was successfully reproduced in simulation. Pressure distributions resulting from the stocking–leg interaction showed clinically consistent patterns, with decreasing pressure from ankle to thigh, and localized peaks around areas with prominent bones.

Overall, this study demonstrates that combining advanced scanning techniques with experimental and numerical modeling enables the development of more realistic and validated compression garment simulations. This framework can support future optimization of stocking design, personalized fitting, and clinical studies focused on compression therapy effectiveness.

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A Step Behind: Occupational Safety and Performance Impacts of Inadequate PPE Footwear for Women

Keywords: PPE, Footwear, Women, Safety, Performance

Research indicates that women are more likely to experience uncomfortable safety footwear than men (Janson, Newman, Dhokia, 2021). Although women have been in occupations like firefighting, law enforcement, and the armed forces for decades, minimal effort has been focused on improving PPE footwear comfort. Many manufacturers attempt to address this problem by creating men's and women's sizes. Unfortunately, too many manufacturers use what is called a "shrink and pink" method, where existing men's footwear models are developed in alternative feminine colorways (e.g. pink) and resized down numerically as the solution for women (Theivam, 2020). This method algebraically is ineffective as women's feet have a shorter heel-to-ball length, narrower ball, instep, heel along with a larger toe region, instep, and medial and lateral malleoli heights (Luo, Houston, Mussman, Garbarini, Beattie & Thongpop, 2009). In addition to sizing and fit, PPE footwear comfort must also consider physiological and biomechanical needs to enable adequate performance. Physiologically, due to hormonal fluctuations, receptor density and surface area women have different footwear flexibility, sensitivity and thermoregulation needs (Hartman, Fehr & Gianakos, 2024; Greenspan, Craft, LeResche, Arendt-Nielsen, Berkley, Fillingim, Gold, Holdcroft, Lautenbacher, Mayer & Mogil, 2007; Burse, 1979). Biomechanically, because women on average weigh less and have a different foot strike, there is a need to engineer sock liner, midsole and outsole shapes/patterns differently (Nigg, Baltich, Maurer & Federolf, 2012, Sinclair, Greenhalgh, Edmundson, Brooks & Hobbs, 2012). Without holistic and accurate consideration of these parameters, PPE manufacturers are putting women at a safety risk. This research will demonstrate considerations in the footwear design process (e.g., form, materials, testing) that can change how PPE footwear is developed for women in the future, ultimately contributing to safer and more inclusive work environments.

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Balancing performance and accessibility: a comparative study of FPCm and JOS-3 human thermoregulation models in various thermal environments

Zhuqiang Hu[a,b], Agnes Psikuta[a*], René M. Rossi[a,b]

[a]*Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, CH-9014, St. Gallen, Switzerland* [b]*Department of Health Science and Technology, ETH Zürich, 8057 Zürich, Switzerland*

Abstract

Human thermoregulation models play a crucial role in predicting physiological responses across various environmental conditions and have been widely applied in fields such as clothing and building design, occupational health and safety, and thermal comfort assessment. Among them, the FPCm model (a commercial model) and the JOS-3 model (an open-source alternative) are two of the most extensively used multi-segment models. This study comprehensively compared these two models, including their historical development, fundamental structure, passive heat transfer mechanisms, and active thermoregulatory controls. The performance of both models was systematically evaluated against experimental data from literature, covering five steady-state thermal conditions (cold, cool, neutral, warm, and hot), two dynamic high-temperature conditions, and two extremely cold environments requiring cold protective clothing. Results indicated that both models exhibit high predictive accuracy and reliability in simulating core and mean skin temperature. In steady-state and dynamic environments, core temperature prediction bias does not exceed 0.38°C, mean skin temperature bias remains within 1.0°C, and root mean square errors for both below 1°C. However, the FPCm model demonstrated superior accuracy under extreme cold conditions, aligning more closely with experimental data. Additionally, the FPCm model provided more accurate predictions for local skin temperatures in transient high-temperature scenarios, particularly on the forehead and hand. While both models are valuable and effective tools for thermo-physiological simulations, the study highlights their respective strengths and limitations. The FPCm model benefits from extensive validation and refinement but remains a closed-source system, limiting accessibility for modification and expansion. In contrast, JOS-3 model as an open-source system, offers greater flexibility for research, adaptation, and further development at the cost of lower accuracy and smaller application range. This study highlights the trade-offs between model accessibility and accuracy, emphasizing the need for further research, development and improvement to enhance the accuracy and applicability of human thermoregulation models in wide range of disciplines.

Practical on-site calibration for multi-sensor passive manikin in human thermal comfort and safety research

Zhuqiang Hu[a,b], Agnes Psikuta[a*], René M. Rossi[a,b]

[a]*Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, CH-9014, St. Gallen, Switzerland* [b]*Department of Health Science and Technology, ETH Zürich, 8057 Zürich, Switzerland*

Abstract

High-resolution spatial and temporal measurement of air temperature and air speed around human body is critical for assessing human thermal comfort and safety in built environments, transportation cabins, and industrial workspaces. The multi-sensor passive HVAC manikin mounted with 46 pairs of air temperature and speed sensors provides an advanced tool for characterizing thermal exposure and as a data source for simulation tools for thermal physiology and thermal sensation. However, despite initial calibration by the manufacturer, systematic errors can arise due to residual heat from internal electronics, sensor placement constraints (hot-bead air speed sensor is 2 cm apart from temperature sensor), and long-term use. Since detaching sensors for calibration is impractical, an effective on-site calibration method is essential to ensure data reliability.

This study proposed a practical on-site calibration method for both types of sensors. For temperature, the manikin was placed in a climatic chamber with a stepwise temperature increase from 0°C to 40°C. Reference sensors positioned near the manikin sensors tracked discrepancies. Two calibration strategies were implemented: correction of sensor readings based on local sensor site temperature and correction of sensor readings to ambient temperature. For air speed, an in-house portable setup using a mini electric fan and adjustable spacers was developed and validated using reference anemometers with the individualized calibration curves for each sensor. The results indicated that temperature variations reached up to 2 °C due to residual heating of electronic elements. After calibration, 41 out of 46 sensors met the accuracy of ±0.2°C, the remaining 5 achieved±0.5°C. For air speed, discrepancies before calibration reached up to 1.40 m/s at 2.24 ± 0.07 m/s. The regression analysis confirmed a strong correlation ($R^2 > 0.96$) between manikin sensor readings and reference values, with a post-calibration accuracy of ±0.085 m/s within 0.1-2.5 m/s. Moreover, sensitivity analysis combined with the thermo-physiological model revealed that inaccuracies in air speed are the primary factor influencing thermal responses. The proposed on-site calibration method enhances the reliability of sensor data, making the multi-sensor passive manikin a more effective tool for research and practical applications in human thermal comfort and safety studies across diverse environmental settings.

Keywords: HVAC manikin, On-site calibration, air temperature, air speed, thermal comfort assessment

Complementary manikins for detailed heat and mass transfer measurements at human body

Agnes Psikuta[*a], Zhuqiang Hu[a,b], Stanislaw Kocik[c], Cheng Gao[a,b], Yan Liang[a,d]

[a]*Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, CH-9014, St. Gallen, Switzerland*

[b]*Department of Health Science and Technology, ETH Zürich, 8057 Zürich, Switzerland*

[c]*Silesian University of Technology, Department of Heating, Ventilation and Dust Removal Technology 44-100 Gliwice, Poland* [d]*Laboratory of Integrated Comfort Engineering, EPFL Fribourg, 1700 Fribourg, Switzerland*

Abstract

Demand of energy reduction and simultaneous enhancement of thermal comfort in human occupation spaces requires sophisticated tools that characterize detailed thermal processes in human proximity. Thermal manikins are frequently used for quantification of the heat and mass transfer processes at the human body surface and through the clothing with high spatial resolution corresponding to manikin segmentation. Modern and most advanced manikins count up to 35 thermal zone reflecting typical body division in human thermoregulation models and enable direct transfer of data for human simulation. On the other hand, they do not have a direct capability to differentiate between different heat transfer modes as they measure total heat transfer only.

In our lab we apply a combination of a thermal sweating manikin ANDI and a passive multisensor manikin – so called HVAC manikin to determine experimentally detailed heat and mass transfer at human body surface. The thermal sweating manikin ANDI is able to typically measure total heat dry exchange between the environment and the manikin heated to a temperature similar to human body. When sweating is added during the measurement, an evaporative heat loss is determined for the assumed sweat rate distribution. The conductive heat exchange occurs at the contact surface with the solid surfaces and can be quantified precisely as long as the contact surface corresponds to the manikin segmentation. If the temperature of the contact surface exceeds the manikin surface temperature, ANDI manikin can still quantify the induced heat gain thanks to its integrated surface heat flux sensor and active cooling system unlike other thermal manikins. The HVAC manikin with 46 sets of temperature, air speed and radiant heat flux monitors the proximal environment of the human body and enables experimental separation of radiant and convective heat transfer shares in a total dry heat transfer measured by ANDI manikin. The combination of both manikins gives an opportunity of experimental investigation of all heat transfer modes present in human thermal exchange with the surroundings in wide range of applications including indoor environment, transportation cabins, occupational settings, personal comfort systems as demonstrated in several study examples.

Keywords: Thermal manikin, multi-sensor manikin, human exposure, heat and mass transfer

Understanding clothing insulation in multilayer ensembles with the help of virtual tools

Lena Parvus[a,b], Agnes Psikuta[a*]

[a]*Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, CH-9014, St. Gallen, Switzerland* [b] *University of Reutlingen, Texoversum, 72762 Reutlingen, Germany*

Abstract

Clothing insulation is dependent on the enclosed air in the clothing system and the fabric properties. However, thermal resistance of the stagnant air is higher than that of common fabrics. The effect increases with multiple air layers in one clothing system, which is especially important for complex multi-layer clothing such as protection wear. Until now, the evaluation of parameters regarding the insulation, e.g. air gap thickness and contact area between body and garment, was often done using 3D body scanning and post-processing software. However, this process faced various challenges, especially with multi-layer clothing and complex body postures, because the scanners cannot capture every detail, resulting in artifacts and inaccuracies. Thus, 3D simulation was used for the same procedure and showed reliability for simple clothing and body poses.

In this study we evaluated two multi-layer clothing systems in complex body postures, using the design software CLO3D and the surface inspection software Geomagic Control. The manikins of the previous study were converted to avatars and the garments were reproduced in CLO3D while the distances between avatar and garment were determined in Geomagic Control. The air gap thickness and contact area compared to the 3D scan data proved that the values concurred for most of the investigated body parts. However, the divergence increased with the level of complexity of the body postures. Furthermore, the distribution of inner material layers and the thermal and evaporative resistance of the firefighter jacket in four body postures were investigated. They showed significant changes when the body posture differed. The thermal and evaporative resistance also changed with different body postures and correlations were found. These findings provide knowledge about the insulation properties of multi-layer clothing and help optimize the validation of the 3D simulation software.

Keywords: clothing model, CLO3D software, thermal resistance, thermal comfort

Assessment of posture and mobility to improve the outer layer design of Korean military cold weather jackets

Ho-Joon Lee[1], Minhee Lee[2], Sang-Hyun Roh[2], Maria Stenkina[1], Do-Hyung Kim[3], Joo-Young Lee[1,2]
Research Institute for Human Ecology, Seoul National University, Seoul, Korea[1]

Department of Fashion and Textiles, Seoul National University, Seoul,

Korea[2] K2 Korea, Seoul, Korea[3]

This study evaluated newly designed military cold-weather outerwear using posture and mobility protocols. The mobility protocol simulated combat scenarios, including shooting, crawling, grenade throwing, and sprinting. Nine male subjects (24.4 ± 3.2 y of age, 175.6 ± 3.2 cm in height, and 74.3 ± 8.3 kg in body weight) participated in the following three clothing conditions: Control, Improved A, and Improved B. Improved A and B featured modifications in size, hood design, seams, and zippers. Posture assessments were conducted across 18 different postures. All assessments took place in an indoor facility (air temperature: 19 ± 1°C; air humidity: 45 ± 4%RH). Heart rate, clothing microclimate temperature/humidity, and subjective responses were measured. After completing all tests, subjects were interviewed using a structured questionnaire. Results revealed significant differences in arm and waist restrictions among the three conditions ($P < 0.05$), with the Control condition showing greater restriction than the two improved designs. During the mobility test, subjects reported less discomfort with Improved A compared to the other two conditions ($P < 0.05$). No significant differences were found in heart rate or trunk microclimate among the three outfits. Interview responses highlighted issues with Control, such as restricted fit, hood discomfort, impaired visibility, and insufficient length. In contrast, Improved A and B enhanced psychological comfort, suggesting potential benefits for combat and training performance. These findings underscore the importance of ergonomic and functional improvements in military outerwear to optimize operational efficiency and user satisfaction.

Physical and physiological properties of waterproof and breathable jackets with PFAS-free membrane

Suhyeon Yeom [1], Ho-Joon Lee[2], Sang-Hyun Roh[2], Do-Hyung Kim[3], Joo-Young Lee[1,2]

Department of Fashion and Textiles, Seoul National University, Seoul, Korea[1]

Research Institute for Human Ecology, Seoul National University, Seoul, Korea[2] K2 Korea, Seoul, Korea[3]

PFAS, used for water repellency in outdoor clothing, do not naturally degrade and can accumulate in the human body through soil and other environmental pathways when outdoor gear is discarded. This accumulation is known to potentially disrupt hormones, suppress the immune system, and increase the risk of cancer. Various outdoor clothing incorporating PFAS-free water-repellent technologies have been developed and are currently available on the market. However, evaluations of the wearability of these products remain limited. Therefore, we collected commercially available PFAS-free outdoor jackets and examined their physical properties and physiological responses through human wear trials. Firstly, using a thermal manikin (Newton, 20-zones), we analyzed the physical properties of four water-resistant and breathable jackets using PFAS membranes (Salomon, Florence, Kolon, and K2) and three jackets using PFAS-free membranes (Patagonia, Arcteryx, and K2). Secondly, we selected four of the seven jackets (one PFAS-based, and three PFAS-free) for human wear trials in a climate chamber. Eight males participated in the four jacket conditions (age 27.4 ± 3.6 y, height 173.8 ± 4.8 cm, and weight 71.5 ± 6.1 kg), and a trial consisted on 10-min rest, 30-min exercise, and 20-min recovery). Despite differences in jacket masses (276 to 717 g), there were no marked differences among the jacket types (I_{cl}: 0.300–0.388 clo, Re,t: 0.048–0.057 kPa·m²/W). Human wear evaluation also revealed no significant differences among the four jacket conditions in auditory canal temperature, mean skin temperature, heart rate, thermal sensation, and thermal comfort. In summary, there were no notable differences in the physical or physiological characteristics of commercially available outdoor jackets regardless of whether they used PFAS or PFAS-free membranes. These results suggest that wearing environmentally friendly PFAS-free jackets may not negatively affect wearing comfort when comparing to outdoor jackets with PFAS membrane.

Breaking the Fit Barrier: Failures in Anthropometric and Patternmaking Applications for PPE Sizing

Kayna Hobbs-Murphy, Ph.D.

Affiliation: Colorado State University, Department of Design and Merchandising, 1574 Campus Delivery 80523

Contact: Kayna.Hobbs-Murphy@colostate.edu

Abstract

Personal Protective Equipment (PPE) is critical to worker safety across industries, yet much of it continues to be designed and sized based on outdated and narrow body standards. Research has consistently shown that ill-fitting PPE increases injury risk, particularly among women, largerbodied workers, petite workers, and disabled workers. However, structural factors within manufacturing and supply chains have limited progress toward more inclusive sizing practices. This paper examines the consequences of persistent sizing gaps in PPE and outlines the technical expertise required to address them. Drawing from professional domains including apparel patternmaking, garment technology, anthropometrics, and occupational health and safety, the analysis demonstrates how translating body diversity into functional protective equipment demands specialized skills across measurement, design, and ergonomic assessment. Improving PPE fit across diverse body types is both a technical and structural challenge, requiring the integration of precise knowledge at every stage of design and production to ensure equitable and effective worker protection. Keywords: Personal Protective Equipment (PPE); Anthropometry; Apparel Patternmaking; Sizing Systems; Occupational Health and Safety

Introduction

Personal Protective Equipment (PPE) serves as a critical safeguard for worker health and safety across industries. However, the sizing systems used to develop PPE remain rooted in outdated anthropometric models that fail to reflect the diversity of the modern workforce. Despite decades of research demonstrating that ill-fitting PPE increases injury risk, comprehensive improvements in sizing practices have been slow to materialize. Current PPE is often developed using limited datasets, historically based on military populations such as the original Anthropometric Survey of U.S. Army Personnel (ANSUR) (Gordon et al., 1989). Although updates such as ANSUR II (Gordon et al., 2014) have attempted to capture broader trends, these limited-population (i.e., military population) datasets still do not fully represent the range of body sizes, shapes, and functional needs present in today's workforce, particularly among women, larger-bodied individuals, petite workers, and disabled workers.

Equipment such as respirators, gloves, harnesses, and protective garments often fail to properly seal, distribute pressure, or allow movement when improperly sized (Zhuang et al., 2011; Golden & Peters, 2021; [redacted] 2021; [redacted] 2025). These outcomes disproportionately affect workers outside traditional sizing norms, exacerbating occupational health disparities. Addressing these challenges requires a detailed understanding of anthropometric variation and garment pattern engineering. Proper fit involves more than scaling existing designs; it requires nuanced adjustments to accommodate nonlinear body changes, movement dynamics, and functional needs. Without this expertise, PPE cannot adequately serve a diverse workforce. This paper highlights technical challenges in PPE sizing, critical failure points in conventional size grading, and proposes a framework for integrating anthropometric data with applied apparel design knowledge to better protect workers across body types.

Methods

This analysis draws on established anthropometric datasets, evaluations of PPE sizing standards, and technical pattern engineering methodologies from apparel design. Key references include the 1988 Anthropometric Survey of U.S. Army Personnel (ANSUR) and ANSUR II (Gordon et al., 1989; Gordon et al., 2014), as well as research on PPE fit and dimensional variability (Hsiao et al., 2009; Zhuang et al., 2011). The approach reflects the author's combined expertise in occupational health and safety—holding a Ph.D. with a focus on ergonomics—and over fifteen years of professional practice in garment patternmaking and apparel design. Through interdisciplinary synthesis, two overarching categories of fit-related design failures were identified, grounded in both anthropometric evidence and applied apparel engineering principles relevant to PPE functionality and worker protection.

Results Dimensional Misfit from Uniform Scaling

Simplified scaling methods frequently assume that all body dimensions increase at the same rate. In practice, many PPE products are resized using percentage-based changes to a base pattern, without accounting for the independent variability of different body segments. However, anthropometric research shows that finger length does not increase proportionally with palm width, nor does leg length predict waist circumference or shoulder breadth correlate linearly with torso depth (Gordon et al., 1989). When this assumption of proportional growth is applied to garments, gloves, helmets, and harnesses, the resulting fit may appear adequate in terms of overall measurements, but often fails to provide proper articulation, coverage, or stability. For example, scaling men's PPE patterns to create "female versions" typically results in garments that are too loose in the waist and lower leg, failing to account for differences in hip proportion and leg taper. This poor shaping can interfere with gait and stability, increasing the likelihood of slips, trips, and falls. In gloves and boots, uniform scaling leads to bulkiness in areas that require dexterity or precision, compromising both safety and performance.

Inadequate Accommodation of Dynamic Movement

Conventional sizing systems rely heavily on static anthropometric measures, such as chest circumference or inseam length. Yet PPE is worn in contexts that demand constant movement—bending, twisting, squatting, reaching—each of which temporarily alters body volume, surface area, and the position of anatomical landmarks. Fit that appears acceptable in a neutral standing pose may restrict range of motion or shift hazard protection zones during active use. Dynamic fit issues are especially dangerous in equipment where seal integrity, coverage, or ergonomic performance are critical. Ill-placed seams or rigid materials can cut into the body during movement, causing pressure injuries or garment displacement. Incorporating gussets in areas such as the armscye, elbow, or pant rise is a common strategy in performance apparel, but remains underutilized in many PPE categories. Design solutions that anticipate mobility—rather than react to misfit—are critical to ensure that PPE supports, rather than hinders, task performance and injury prevention.

Shape Misalignment from Grading Oversimplification

Even when PPE products are offered in multiple sizes, many rely on grading systems that fail to preserve body-shape logic across the size range. Grading refers to the process of creating a range of sizes from a base pattern using a set of mathematical rules. Unlike uniform scaling, grading typically applies different increments to different body zones—such as adding more to girth than to length—but it still often assumes that the shape of the body remains constant as it changes in size. In reality, bodies do not simply grow or shrink in fixed ratios. Features like bust apex, shoulder slope, armhole depth, waist shaping, and hip curvature all shift disproportionately across size ranges. This means that even well-intentioned grading systems can result in garments that distort the original pattern's intended fit or functionality. For example, if a PPE jacket is graded up without adjusting the shoulder angle or bust position, it may technically "fit" larger bodies in circumference, but fall incorrectly on the torso, restricting movement or gaping at closure points. Similarly, pants may gain circumference but fail to adjust crotch depth or rise positioning, resulting in chafing or garment slippage. These shape misalignments are not the result of simplistic uniform scaling (as described in Theme 1), but of grading systems that apply mathematically consistent, yet anatomically unresponsive, rules. Importantly, many grading systems used in PPE design are adapted from ready-to-wear apparel practices that prioritize manufacturability and efficiency over ergonomic integrity. Without detailed pattern engineering that accounts for proportional body changes, PPE grading reinforces the same fit failures seen in underperforming consumer garments—only with much higher stakes for wearer safety and task performance.

Discussion and Conclusion

This analysis demonstrates how conventional PPE design practices—shaped by outdated anthropometric models and oversimplified sizing strategies—undermine protection for a wide range of workers. Fit failures result from three critical issues: assuming proportional scaling across body dimensions, ignoring the effects of dynamic movement on fit and protection, and applying grading systems that distort anatomical accuracy across size ranges. These design shortcomings disproportionately affect women, larger-bodied individuals, petite workers, and disabled populations—those most frequently excluded from traditional sizing models.

Improving PPE fit demands interdisciplinary integration. Anthropometric data must be applied with nuance, beyond population averages. Apparel patternmaking expertise is essential for interpreting body shape variation and translating it into functional garment structures. In addition, professionals in occupational safety and product design should receive training in garment fit principles to close the communication gap between disciplines. Procurement standards must also evolve to prioritize fit testing and inclusive sizing—not just basic provision.

Although PPE innovation often emphasizes materials or hazard resistance, the field of apparel design—particularly plus-size and adaptive apparel—has long addressed challenges of non-linear body growth, shape variability, and dynamic fit. These design strategies remain largely untapped in PPE development. Closing this disciplinary divide is critical to ensuring not just improved safety outcomes, but equitable protection for all workers. This paper offers a technical and conceptual framework to support that shift. Future research should continue advancing inclusive fit standards through empirical evaluation, digital simulation, and applied design testing. Advancing fit equity in PPE design requires not only better data, but deeper integration of patternmaking and ergonomic expertise across development pipelines.

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Characterizing localized thermal insulation of gloves at the fingertip using a sensor-integrated hand manikin and infrared thermography

Mengying Zhang, Rui Li, Jie Yang, Fan Zhou, Yulin Wu, Guowen Song

Effective hand protection in cold environments requires accurate evaluation of glove thermal insulation. However, traditional thermal hand manikin typically measures only the overall thermal resistance for an entire finger, failing to capture variations across the finger. Fingertips, in particular, experience the greatest heat loss and often exhibit the lowest temperatures, making them especially vulnerable to cold injuries. Therefore, a more detailed measurement, focusing on the fingertip, is needed to guide glove design optimization, enhance dexterity, and prevent cold injuries.

This study introduces a novel approach using a sensor-integrated thermal hand manikin to quantify local insulation at the fingertip. Flexible miniature heat flux and temperature sensors were placed on the nailbed and the distal, middle, and proximal phalanges of the manikin's little finger. Simultaneously, infrared (IR) thermography recorded the external surface temperature of the gloved finger. The thermal hand manikin maintained a constant surface temperature of 35 °C during the experiment, generated heat flux was recorded as well. Thermal data from the embedded sensors and the IR thermography was used to calculate sectional thermal insulation across the finger sections.

Infrared thermography revealed significant temperature differences along the finger: the distal phalanx had a markedly lower surface temperature than the middle and proximal phalanges, indicating greater heat loss at the distal phalanx section. The nailbed was even colder than the distal phalanx, identifying it as the region of highest heat loss. Significant differences in insulation across the finger section. The nail bed and distal phalanx consistently showed lower thermal resistance than the middle and proximal phalanges. This indicates that the fingertip sections are less insulated and lose heat more rapidly under a glove, confirming long-suspected vulnerabilities in glove coverage.

Combining embedded sensing with IR imaging provides a high-resolution, non-invasive method to assess localized glove thermal performance. By identifying areas of reduced insulation at the fingertips, this integrated technique enables targeted improvements in glove design and engineering to reinforce insulation in these vulnerable regions. This targeted improvement helps prevent cold-induced injuries and preserves manual dexterity by optimizing the balance between thermal protection and flexibility.

Keywords: Thermal resistance; hand manikin; glove design; heat flux sensors; cold weather injury

Impact of Humidity on the Thermal Resistance of Ski Gloves.

Yazid Kaced, Decathlon SportsLab

While a lot of work has been carried out in determining the thermal properties of textile materials, much remains to be investigated when examining how moisture content affects the thermal resistance (Rc) of finished products. The main goal of this work is to address this research's gap by evaluating how sweating influences the ski glove's thermal resistance (Rc).

The test is conducted under two different conditions: dry (measuring thermal resistance via dry gloves) and wet (measuring total heat transfer in gloves with artificial sweating). The test conditions are: 5°C ambient temperature, 30°C hand temperature, 55% relative humidity, and 3.33 $m.s^{-1}$ wind speed. The rate of sweating is set at 200 $ml.m^{-2}.h^{-1}$ (approximately 85 ml over a period of 7 to 8 hours), which represents average hand sweating rates during physical exertion.

To determine the Rc of wet gloves appropriately, we use a thermal balance method in this study. We measure the total amount of water used and the amount remaining in the glove after the experiment. The difference between these two represents the amount of water evaporated. From this evaporated water amount, we determine the evaporative flux with evaporative flux being distinguishable from total heat flux. Evaporative component was calculated through the formula: Evaporative Flux = $m \cdot Cp$, where "m" is the rate of water vaporization ($kg.s^{-1}$) and "Cp" is the water specific heat during the vaporization phase ($kJ.kg^{-1} \cdot K^{-1}$).

The results show a significant reduction in thermal resistance that was evident when the glove was saturated, a maximum possible decrement of 25%. There were, however, a number of drawbacks found: inability to measure wet thermal resistance across various areas, difficulty measuring higher flow rates in accordance with water runoff, and a longer time required in order to generate sufficient amounts of water to reach a steady state condition.

Future studies should include longer test durations to obtain more data on water uptake, measure water capacity of a glove, and determine the relationship between water content and lower Rc in a range of glove types.

Keywords: Thermal resistance, Sweating thermal manikin, Protective gloves, Humidity effect, Thermal comfort

Two-Dimensional CFD Simulation of Steady-State Dry Heat Loss from a Clothed Human Torso Using Fabric-Covered Cylindrical Models

Zubieda Alali and Steven Eckels, Kansas State University

By integrating CFD modeling with fabric property characterization, this study offers a practical and precise tool for evaluating clothing systems. Ultimately, these simulations contribute to refining the selection of fabric transport properties to ensure thermal comfort while providing adequate protection. Understanding thermal transport in clothing systems is essential for enhancing human thermal comfort and protection across various environmental conditions. This study proposes a two-dimensional computational fluid dynamics (CFD) model to simulate steady-state dry heat loss from a clothed human torso. The model utilizes fabric-covered cylinders as realistic alternatives for human body segments, providing a computationally efficient and experimentally feasible geometry to examine heat transfer mechanisms in clothing systems.

Fabric-covered cylinders effectively represent clothing assemblies, capturing critical features such as fabric-air layering, thermal insulation, and surface curvature. This geometric simplification offers a well-defined experimental and computational framework, allowing for thorough analysis without the high computational costs associated with accurately modeling clothed human figures. While substantial progress has been made in modeling the true geometry of clothed human bodies, the significant computational expense of such simulations restricts their use for research studies that look at different variables.

In this research, the CFD model is compared to laboratory evaluations, including hot plate measurements and thermal manikin tests conducted in environmental chambers. Material properties such as thermal conductivity and fabric structure were incorporated into the model. Simulations were conducted with a constant cylinder surface temperature of 35 °C—representative of human skin—against an ambient air temperature of 5 °C. External air velocities ranging from 0.05 to 6 m/s were considered to capture convective effects under still and windy conditions. The model also integrates thermal radiation heat transfer within the fabric and air gap to create a realistic total heat transfer mode. The fabric layer was modeled as a porous medium to realistically account for its complex internal structure. The bare cylinder case was included as a baseline for validation, with results demonstrating strong alignment with classical heat transfer correlations for crossflow over heated cylinders.

Simulation results indicated that, across a wide variety of clothing fabrics, the thermal resistance to dry heat transfer scales proportionally with fabric thickness, consistent with previous literature findings. Furthermore, the simulations provided valuable insights into the impact of air gaps and varying spacing between the fabric and skin surface, which significantly affect heat transfer efficiency. These findings support the continued utilization of fabric-covered cylinder models as effective substitutes for more complex geometries in the study of clothing thermal performance.

Additionally, the model allows for direct comparison with standardized thermal insulation values (clo units), which range from 0 clo (nude body) to approximately 2 clo for ensembles such as the standard U.S. Army uniform, as referenced by ASHRAE and other thermal comfort guidelines.

Colorants as Green Functional Agents for Environmentally Friendly Personal Protective Textiles

Yufa Sun and Gang Sun
Department of Biological and Agricultural Engineering, University of California, Davis, CA 95616, USA

Keywords: Chemical and biological protective, photosensitizers, colorants, sustainable

Novel personal protective textiles can provide various functions such as antibacterial, antiviral, self-cleaning, UV-protective, detoxifying, fire, and thermal protection for different professions and the public with advanced technologies. Many of the functions are currently achieved by incorporating reactive functional agents into polymers or fibers, especially in the development of active chemical and biological protective materials. The use of these chemical agents in textile products with close skin contacts and respiratory access could bring human safety concerns, and production and disposal of such materials may have environmental consequences. Thus, the adaptation of green chemistry and sustainable technologies in the development of personal protective textiles has been highly desired and a challenge to researchers. In recent years, we have been exploring the possibility of employing colorants as functional agents and daylight as a driving force in design and preparation of light-induced functional fibers and polymers. These colorants could be traditional textile dyes or pigments and can be edible vitamins with colors. The unique features of these chemicals are that they are photosensitizers, and the reactive functions are fully based on exposure to daylight without additional energy inputs. This presentation will illustrate the photochemistry of colorant photosensitizers and provide several successful examples of light induced functional fibers and textiles.

An Evaluation of Thermal Insulation of Protective Gear on Firefighter Heat Strain

Mushfika Mica, Emiel DenHartog, Roger Barker, and Anthony Deaton
North Carolina State University

ABSTRACT

INTRODUCTION: Between 2019 and 2024, 122 incidents occurred in the USA where firefighters were shot and killed while responding to active-shooting scenarios. After firefighters became targets of violence, fire departments requested funds to make ballistic vests standard personal protective equipment (PPE). Research studies indicate the potential harmful impact on firefighter heat strain when adding additional layers and thickness to the turnout gear [1]. Wearing ballistic vests with turnout gear may not only increase the risk of heat strain [2] by reducing heat dissipation but also contribute to discomfort, restricting movement and increasing sweat accumulation due to increased thermal insulation. Thermal insulation measures the ability of a material or system to reduce the transfer of heat.

MATERIALS AND METHODS: To quantify the thermal insulation, six firefighting ensembles were tested using thermal male manikin: E1) station uniform; E2) station uniform+ballistic vest; E3) station uniform+turnout suit; E4) station uniform+turnout suit+ballistic vest worn under turnout jacket; E5) station uniform+turnout suit+ballistic vest worn over turnout jacket; E6) station uniform+turnout suit+ballistic vest with hard plates.

Test conditions: Dry test was conducted to assess the thermal insulation of the clothing ensembles following the ASTM1291 standard. The mean surface temperature of the manikin was 35 °C ∓0.1 °C. The air temperature, relative humidity and wind speed in the test chamber were 15°C, 45-55%, and 0.4 m/s respectively.

RESULTS AND DISCUSSION: The thermal insulation (Rt) values for E1, E2, E3, E4, E5, and E6 in the torso area were 0.166, 0.331, 0.463, 0.622, 0.652, and 0.631 m2·°C·W−1 respectively. The results evidently depicted a progression of thermal insulation values in the torso area with adding layers. Rt increased from 0.166 m2·°C·W−1 in E1 (baseline-without ballistic vest) to 0.331 m2·°C·W−1 in E2 (with ballistic vest added).

The relative increase in Rt from E1 to E2 is approximately 99%, which indicated twice the thermal insulation with the addition of the ballistic vest. The further increase in Rt through E3 to E6 up to 0.652 $m^2 \cdot °C \cdot W^{-1}$ demonstrated the compounding effect of additional layers in the firefighting turnout ensemble. The substantial increase in Rt from E1 to E2 is due to the dense materials in ballistic vests that is designed to provide ballistic protection that inherently reduced heat transfer. The further increase in Rt through E3 (baseline-without ballistic vest) to E6 was caused by the added layers of turnout suits. The additional layer of ballistic vest in E4, E5, and E6 increased the thermal insulation further. Despite adding hard plates to the ballistic vest in E6, it had a Rt of 0.631 $m^2 \cdot °C \cdot W^{-1}$ which is lower than E5. It indicated that adding hard plates reduced air gaps and created more contact points for heat transfer which led to the lowering of thermal insulation of E6.

CONCLUSION: Firefighters may experience heat strain as a result of the ensemble's reduced ability to dissipate heat, which is directly correlated with the increased thermal insulation provided by the ballistic vest and extra layers. Reduced heat loss from the body due to increased insulation raises core and skin temperatures and boosts cardiac output. In addition to causing physiological strain, this heat accumulation lowers general comfort, which makes it difficult for firefighters to perform their duties effectively. Discomfort from excessive heat and sweat accumulation can contribute to fatigue, decreased focus, and impaired decision-making, further increasing the risk of heat related illness such as heat stroke, hyperthermia and performance degradation.

Comfort of PPE – how can comfort assessment be integrated in a general PPE standard?

Edith Classen
Hohenstein Innovations gGmbH, Bönnigheim, Germany

The determination of comfort of clothing is done using with different test methods and the comfort of clothing can be evaluated. This comfort evaluation is mostly done under standardized methods which simulated the environmental use condition. The test methods are material test methods or product test methods (e.g. ISO 11092, ISO 15381). Results of subject trials are available which confirm that the results of these methods meet the real conditions of use. The evaluation of the comfort of personal protective clothing is often limited because the protection function, often material layers with certain functions are used for safety reasons and these combinations reduce the comfort of such clothing. Personal protective clothing should provide the protection against certain risk (e.g. fire, cold) and at the same time provide the highest comfort as possible for the user. The international standard ISO 13688 specifies the general requirements for protective clothing. These requirements relate to the ergonomics, harmlessness, aging, size designation, and compatibility of protective clothing. This standard is under revision and one important issue is the integration of requirements of comforts properties. Up to now, there are no general requirements for the comfort assessment of PPE available. In some PPE product standards material measurements are required, other product standards use product measurement with manikins. Another important aspect for the PPE testing is the economic situation. Are the existing methods applicable for the assessment of the comfort of PPE? Is it necessary to adapt methods for the situation of the user of PPE? The talk will give an overview about the current discussion in the PPE standardization group to improve PPE by including an adequate test scenario to evaluate the comfort of different personal protective clothing.

Influence of different fabrics on cutaneous thermal sensation under radiant heat exposure in electric vehicles during winter

Sang-Hyun Roh[1], Suhyeon Yeom[2], Joo-Young Lee[1,2]

Research Institute for Human Ecology, Seoul National University, Seoul, Korea[1]

Department of Fashion and Textiles, Seoul National University, Seoul, Korea[2]

To reduce electricity consumption in electric vehicles (EVs) during winter, the development of an in-vehicle localized proximity heating system is being carried out. Car manufacturers are integrating radiant heaters into the vehicle's trim to provide heating according to passengers' needs. However, the risk of skin burns due to prolonged unconscious exposure cannot be ignored. In particular, thermal thresholds on the skin may vary depending on the material of the clothing. Therefore, we explored differences in the perceived warmth, hotness, and heat pain thresholds based on the material of the clothing. The present study consisted of two different experiments. [Experiment 1] Eight males (age: 24.1 ± 3.9 y, height: 178.2 ± 5.7 cm, weight: 74.1 ± 15.6 kg) participated in two conditions: (1) bare skin, and (2) 100% cotton pants. The lateral side of the thigh was exposed to a radiant heat panel (10 × 30 cm^2, 130°C surface temperature) at a 2 cm distance. The climate chamber was maintained at 14.3 ± 0.2°C and 57 ± 1%RH to simulate the interior environment of vehicles parked during winter. [Experiment 2] Seven males (23.8 ± 2.6 y, 175.1 ± 4.3 cm, 81.0 ± 10.5 kg) participated in the following three conditions: (1) 100% cotton, (2) 100% wool, and (3) 100% polyester pants. The identical body region on the left thigh was exposed to the radiant heat panel (10 × 30 cm^2, 135°C surface temperature) at a 10 cm distance, which was the typical distance between the passenger and a thigh heater inside the EV. The climate chamber was maintained at 21.9 ± 0.2°C and 50 ± 1%RH. As a result, cutaneous thermal thresholds showed no significant differences between bare skin and clothed conditions. The cutaneous thermal thresholds for perceiving thermal sensation on the thigh did not differ among the cotton, polyester, and wool pant conditions. Interestingly, the heat flux at the point where thermal thresholds were achieved was the lowest, and the surface temperature of the fabric was the highest for the cotton condition. There was no significant difference in heat flux or surface temperature between the polyester and wool pant conditions.

Experimental study on the Influence of Activity Intensity and Personal Protective Clothing on Human Thermal Responses in Dynamic Hot Environments

Mengyao Huang[1], Ming Fu[1], Jia Wang[1], Liangchang Shen[1], Yayun Li[1], Xuefan Wang[1] and Shifei Shen[1]

[1]Tsinghua University

Abstract: This study aims to investigate human thermal responses in hot environments and the possible factors that influences these responses. A subject experiment was conducted in a dynamic hot environment, with temperatures fluctuating between 25 ° C and 35 ° C. Varying activity intensities of 4 km/h and 7 km/h and three different clothing conditions, including basic clothing, firefighting clothing, and rescue clothing, were also taken into consideration. The main thermophysiological indicators were measured, and the perceptual performance was assessed. The results indicate that increases in ambient temperature and activity intensity can significantly heighten thermophysiological pressure and cause thermal discomfort and fatigue. Wearing high thermal-resistance clothing exacerbates this effect, resulting in elevated levels of heat strain. Implementing intermittent rest periods can substantially improve thermal responses, reducing the heat strain index in terms of physiology and perception by 60% and 93%, respectively. Nonetheless, recovering core temperature requires additional measures. The thermal sensation and thermal comfort under protective clothing conditions statistically correlate with the mean skin temperature. This study is valuable for assessing thermal safety and thermal comfort and developing corresponding predictive models for occupational heat exposures.
Keywords: dynamic hot environment; activity intensity; personal protective clothing; thermal response; subject experiment.

1. INTRODUCTION

As global climate change intensifies, workers face increased threats from occupational heat exposure. Core temperature, skin temperature, and perception performance are key indicators for evaluating comfort and thermal safety [1-2]. Studying these thermal responses in hot environments is crucial for ensuring workers' safety and enhancing their work efficiency. Existing experimental studies on hot environments have several limitations, which are often do not fully account for occupational characteristics, such as the use of personal protective equipment (PPE) and varying levels of physical activity. Additionally, these studies typically concentrate on human thermal responses during stable and continuous work while overlooking the importance of rest periods. This paper aims to conduct a experiment to investigate workers' thermal responses in dynamic hot environments and analyze the effects of temperature, activity intensity, and protective clothing on levels of heat strain.

1 Method

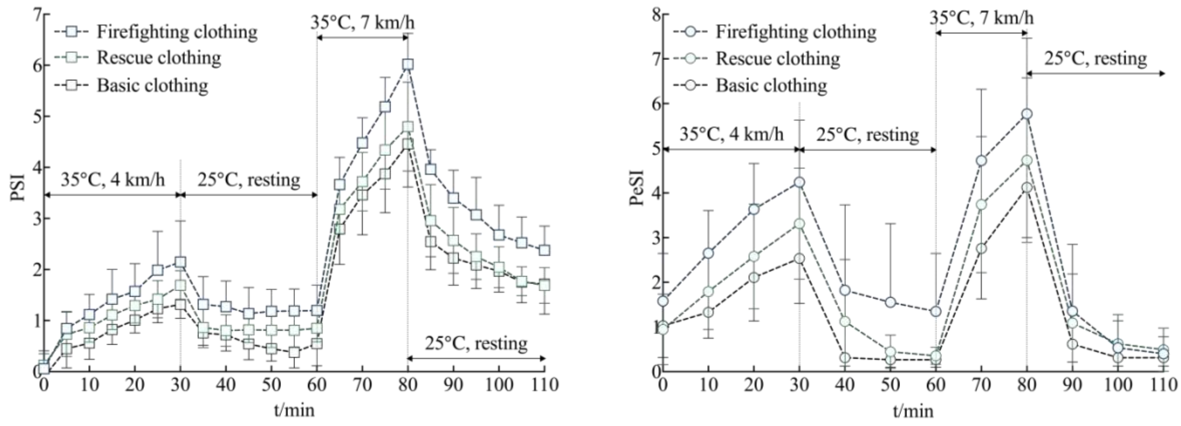
The experiment was conducted in two climate chambers. One chamber served as the working room (T_a=35 °C, RH=45 %, v=0.1 m/s), while the other chamber was designated as the resting room (T_a=25 °C, RH=45 %, v=0.1 m/s). Eight healthy males participated in experiments, which included three clothing conditions: basic clothing (T-thirts & shorts, 0.6 clo), firefighting clothing (2.2 clo), and rescue clothing (1.0 clo). Before the experiment began, the volunteers entered the resting room and sat quietly for 60 min to minimize external distractions. The experiment followed these procedures: 1) Enter the working room and walk on the treadmill at 4 km/h for 30 min. 2) Return to the resting room and sit for 30 min. 3) Re-enter the working room and run at 7 km/h for 20 min. 4) Return to the resting room, remove outer protective clothing such as a jacket, and sit for 30 min. Key thermal physiological indicators, including core temperature, skin temperature, heart rate, and sweating rate, were measured. And perception performance, including thermal sensation (TSV), thermal comfort (TCV), and the rating of perceived exertion (RPE) was recorded. Furthermore, the Physiological Strain Index (PSI) [3] and Perception-based Strain Index (PeSI) [4] were calculated based on these physiological and perception indicators.

2 Results and discussion

Thermal responses are influenced by both the ambient temperature and the activity intensity. As ambient temperature and activity intensity increase, the thermal physiological values rise, combined with greater thermal discomfort and fatigue, leading to higher heat strain, as shown in Fig. 1. Compared to core temperature, the skin temperature and the heart rate are more responsive to changes in ambient temperature and activity intensity. Furthermore, the thermal physiological values increase and the levels of thermal discomfort and fatigue rise as the thermal resistance of clothing increases, leading to PSI=6.02 and PeSI=5.77 for firefighting clothing.

Alternating between periods of activity and resting can help reduce physiological and perceptual heat strain by 60 % and 93 %, respectively. Taking a rest that is the same length as the activity can effectively lower skin temperature and heart rate, and improving thermal comfort and fatigue to ordinary levels. Additionally, removing outer protective clothing can enhance this effect and help shorten the recovery time. However, due to the influence of excess post-exercise oxygen consumption (EPOC), core temperature may remain elevated during the resting phase, making it difficult to recover quickly. This prolonged high core temperature lead to cumulative damage to the body in the long term.

There are linear relationships between PeSI and PSI under three clothing conditions (R^2>0.74), allowing for the development of a straightforward prediction method for PSI. A strong linear relationship exists between the mean skin temperature and both overall thermal sensation (R^2>0.86) and thermal comfort (R^2>0.79) under protective clothing conditions, which is also helpful for developing related thermal comfort models based on skin temperature to assess heat strain in various working conditions.



(a) PSI (b) PeSI

Fig. 1 The variation of MET and HR over time

3 Conclusion

This study conducted experiments to analyze the effect of ambient temperature, activity intensity, and clothing condition on human physiological and perceptual responses. The results show that rise in ambient temperature and activity intensity increases the physiological strain and also leads to greater thermal discomfort and fatigue. Clothing with high thermal resistance exacerbates this issue. The PSI and PeSI decrease obviously after a resting period. However, the core body temperature won't return to normal levels in a short time. It's found a strong linear relationship between mean skin temperature and both overall thermal sensation and thermal comfort. Additionally, a clear linear relationship exists between the PSI and PeSI.

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Possibilities of Measurement with a Thermal Sweating Manikin

Author Names: Bianca-Michaela Wölfling, Edith Classen
Affiliations: Hohenstein Innovations gGmbH
Contact Information: b.woelfling@hohenstein.com

Thermal sweating manikins offer a unique and precise method for evaluating the thermal and evaporative properties of clothing systems. This paper explores the possibilities of measurement using these advanced manikins, focusing on their ability to simulate human sweating and movement. The study aims to provide insights into the effectiveness of different garment designs in managing heat and moisture, thereby enhancing wearer comfort and performance. Methods include controlled experiments in climate chambers, utilizing DIN EN ISO 15831, ASTM F1291, DIN EN 17528, and ASTM F2370 standards. Results indicate significant variations in thermal insulation and evaporative resistance across different clothing ensembles. The discussion highlights the advantages of using thermal sweating manikins over traditional human trials, emphasizing their precision, repeatability, and ability to test under extreme conditions.

Furthermore, the study delves into the implications of these findings for the textile industry, particularly in the development of high-performance sportswear and protective clothing. By simulating real-world conditions, thermal sweating manikins provide a comprehensive understanding of how garments behave under various environmental stresses. This allows designers to optimize materials and construction techniques to achieve better thermophysiological comfort. The paper also addresses the limitations of current testing methods and proposes future directions for research, including the integration of advanced sensors and data analytics to enhance the accuracy and applicability of manikin-based evaluations.

Conclusions suggest that thermal sweating manikins are invaluable tools for optimizing garment design and improving thermophysiological comfort. Their ability to provide consistent and reproducible results under controlled conditions makes them superior to traditional human trials, which can be influenced by numerous variables. As the demand for high-performance clothing continues to grow, the role of thermal sweating manikins in research and development is expected to become increasingly significant.

The Influence of Friction and Pressure Exerted by Weft-Knitted Fabrics on Motion Control

Clothing is an indispensable component of daily life, influencing comfort, functionality, and overall health. Consequently, optimizing garment design by examining the influence of knitted fabric structures on applied friction and pressure distribution is essential for enhancing well-being and performance. A comprehensive understanding of the mechanical behavior of these fabrics allows for the refinement of their design, facilitating improved applications in rehabilitation, sportswear, and other performance-driven domains.

Current research particularly focuses on the areas prone to be under friction and stress during movement. This study employs an experimental approach, developing prototypes of compression arm sleeves with various knitted structures. Key to the experimental setup is the use of a localized friction measurement device, and pressure sensors to analyze fabric-skin interactions. Essential parameters, including friction force and applied pressure, were meticulously measured to evaluate their influence on motion control. Motion control was assessed using a motion capture system and quantified by analyzing the distance between the wrist marker and a designated reference marker. The findings demonstrated that the 1×1 mock rib and 1×1 mock rib with inlay notably enhanced the frictional and pressure properties exerted on the skin, thereby improving motion control. This suggests that elevated frictional forces and applied pressures result in a reduced distance between the wrist and the reference marker, which can be strategically leveraged to optimize stability and refine motion control.

These findings lay the foundation for future advancements in functional clothing design, bridging the gap between textile engineering and human biomechanics. They offer critical insights that drive the innovation of next-generation compression garments, optimizing performance.

Predicting the Effectiveness of Structural Internal Firefighting Gear using Computational Thermal Modeling

Savannah Page[1], Mark Hepokoski[1], Timofey Golubev[1], Kalev Kuklane[2,3]

[1] *ThermoAnalytics, Inc., Calumet, MI, USA*

[2] *Team Fire Service Science, Netherlands Academy of Crisis Management and Fire Service Science, Netherlands Institute for Public Safety (NIPV), Arnhem, The Netherlands*

[3] *Chair of Biosystems Engineering, Institute of Forestry and Engineering, Estonian University of Life Sciences, Tartu, Estonia*

Firefighters are commonly exposed to high radiant temperatures while performing intense physical activity, which can result in significant thermal strain as indicated by elevated body temperatures. It is therefore essential that firefighters wear breathable, but sufficiently protective clothing to keep them safe, without which could lead to severe burns, dehydration, and heat stroke. Previous research has shown that computational modeling can be employed to determine the effectiveness of technical rescue gear. In this study, a computational thermal model was used to reproduce human subject tests comparing two types of firefighter turnout gear in a structural internal firefighting (SIF) scenario.

Human subject testing incorporated nine Dutch firefighters. Four participants wore a traditional set of firefighter turnout gear, SIF-T, and five wore a new system with a double layer jacket, SIFD. An IR radiation panel was positioned to the right of the test person, to achieve 4 kW/m^2 radiation at the right upper arm. The SIF scenario was defined by seven consecutive stages with varied walking intensity on a treadmill and intermittent periods of IR radiation. Rectal temperature, mean skin temperature, heart rate, and oxygen consumption rate (VO2) were recorded.

A human model in the TAITherm™ thermal modeling software was set up to reproduce the SIF test scenarios. The model considers all modes of heat transfer, including latent heat transfer, and contains a sophisticated human thermophysiology model that simulates passive and active thermoregulation. Convection around the human was estimated using the treadmill speed. Measured local clothing properties were applied to the segments of the human body and subdivided into nine discrete layers to capture internal temperature transients over the course of the simulated exposures.

Despite the traditional clothing set SIF-T having a slightly steeper rise in mean skin and rectal temperatures as compared to the SIF-D ensemble, the measured differences between the two ensembles were minor. Model predictions for both ensembles showed good agreement with test data, reproducing the trends and consistently remaining within one standard deviation of skin and core temperature measurements. This study demonstrates the value of using computational modeling for evaluating the effectiveness of structural internal firefighting gear.

Biophysical evaluation of heated casualty hypothermia bags

Madeline Poley-Bogan[1], Timothy P. Rioux, John W. Castellani, and Xiaojiang Xu. Thermal and Mountain Medicine Division, U.S. Army Research Institute of Environmental Medicine; [1]Oak Ridge Institute for Science and Education (ORISE)

Heated casualty hypothermia bags are specialized medical bags that transport injured victims to medical treatment facilities. Hypothermia and cold injury are significant factors during transportation, especially in cold or extreme environments and following trauma. Maintaining body temperature during transport is critical, and battery-powered heated hypothermia bags could be a potential approach to maintain human safety and prevent cold injury during exposure to cold environments. Thus, the objective of this study was to evaluate the thermal resistance (clo) and heating performance (W) of heated casualty hypothermia bags at three power settings – low, medium, and high – using a whole-body, dynamic sweating thermal manikin. Four bag configurations were tested in a controlled environmental chamber, with environmental conditions set to an air temperature of 6°C, 55% relative humidity (RH%), and air velocity of 0.3 m·s-1. The heated bags were evaluated using a nude manikin positioned horizontally on a cot, with measurements collected according to ASTM F1720-17. The manikin's Dynamic Heat Flux Sensors (DHS) and internal cooling system were utilized, allowing for negative (gaining heat from the environment) heat flux measurements with the addition of an external heating system. The average heating power for Bag A, Bag B, Bag A with Outer Insulation, and Bag B with Outer Insulation were 14.9W, 6.1W, 11.9W, and 5.6W, respectively. Results showed an increase in thermal insulation as the heating power levels increased. Additionally, results also demonstrated a decrease in heating power (W) as outer insulation was added, indicating that it requires less power to maintain the same temperature. Backside cooling system appears to reduce variations of measured parameters, however, its impact on measured results and benefits require further research.

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Predicting Human Thermal Responses During Exercise in Heat and Cold Using
Finite Element Thermoregulatory Models

Stefan Gutierrez[1,2], Juliette Jacques[1,2], Timothy Rioux[1], Gabrielle E Giersch[1], Afton D Seeley[1], John Castellani[1], Xiaojiang Xu[1]

[1]US Army Research Institute of Environmental Medicine, Natick, MA, US

[2]Oak Ridge Institute for Science and Education (ORISE), Oak Ridge, TN, USA

Introduction

Recently, two geometry-specific finite element thermoregulatory models (FETM) with medical image-based geometry were successfully developed (Castellani et al., 2021; Castellani et al., 2023) and validated primarily in resting conditions. This investigation aims to further validate FETM predictions against physiological data collected during exercise in hot and cold conditions.

Methods

The FETMs were developed in a finite element software (COMSOL Multiphysics). Model predictions were validated with physiological data collected during exercise in hot and cold conditions. Dataset 1: Twenty-nine volunteers walked on a treadmill at an average 359W (estimated by Pandolf equation) for 120 minutes in a 40ºC, 40% relative humidity environment wearing military PT clothing. Core (T_{core}) and four skin temperatures (T_{sk}) were collected. Dataset 2: Twelve adults wearing different military ensembles completed three trials in 5°C air. Volunteers rested for 60 min followed by two 60 min walks at an average 347W and 382W. T_{core} and eleven site T_{sk} were collected (Seeley et al., 2024). Differences between observed values in T_{core} and T_{sk} were evaluated by comparing root mean square deviations (RMSD) with observed standard deviations (SD). If RMSD was less than SD, predictions were considered valid.

Results

In 40°C conditions, predicted T_{core} was within observed values towards the end of experiment and the predicted chest T_{sk} were within the mean ± SD. RMSD were 0.37°C and 0.19°C for core and chest temperatures, respectively. Observed SD for core and chest temperature were 0.40°C and 0.66°C, respectively.

In 5°C wet clothing conditions, predicted T_{core} were below the observed values by an average 0.76°C. Predicted T_{sk} were within the mean ± SD. RMSD was 0.84 °C and 1.27°C for T_{core} and T_{sk}, respectively. Observed SD for core and skin temperature were 0.4°C and 1.25°C, respectively.

Discussion/Conclusion

Predicting high resolution temperature distributions enable better understanding on how to improve human thermoregulation. Our validation demonstrates that the models predict spatial temperature with acceptable accuracy in hot exercising conditions. In cold conditions with wet clothing, the FETM predicted skin temperature with acceptable accuracy; however, core temperature was underpredicted. Further investigation needs to be conducted to understand why.

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Human Thermal Modeling of Patients Under General Anesthesia

Mark Hepokoski (ThermoAnalytics)
Alexia Canull (ThermoAnalytics)
Carlos Guerra-Londono (Department of Anesthesiology, Pain Management, & Perioperative Medicine, Henry Ford Hospital)

Introduction

Anesthesia modifies thermoregulatory function by adjusting the temperature threshold, gain and maximum intensity of shivering, vasomotion and sweating [1] [2]. Anesthesia also reduces metabolism [3]. General anesthesia exhibits a characteristic pattern, described by three consecutive stages of core temperature progression: 1) a rapid drop; 2) then a slower, nearly linear decrease; and finally, 3) stabilization to a plateau [4].

Methods

A thermophysiology model significantly enhanced from [5] was adapted to reproduce the characteristic pattern described above. This was accomplished by adjusting model parameters in the passive and active systems. Tissue metabolic rates were reduced throughout the body, which consequently lowered the temperature setpoints for active thermoregulation. Shivering was disabled. The threshold for vasoconstriction was lowered to correspond to the predicted skin temperature at which the plateau in core temperature was anticipated to form.

Results & Discussion

The model reproduced the desired trends, with core temperature predictions within one standard deviation of measurements. The lower setpoint temperatures temporarily maintained vasodilatation during the first hour, which facilitated a rapid drop in core temperature, consistent with observations. This was followed by a slower, nearly linear decrease, which eventually leveled off to a plateau after the onset of vasoconstriction.

Conclusion

The model provided detailed thermal and thermophysiologic response predictions during the three stages of general anesthesia-induced hypothermia, which would be difficult to derive exclusively from measurements. Notable was that the slower, nearly linear decrease in core temperature observed prior to the plateau appears to indicate a complete pause in active thermoregulatory function, which is reproducible in simulation by considering the passive system alone in the human thermal model.

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Analysis of Thermal Comfort in Phase Change Cooling Vests with Variable Melting Points

Miriam Martinez-Albert1[1*], Eva Bou-Belda[2]

[1]Comfort Department, Textile Industry Research Association-AITEX, Alcoy, Spain.

[2]Departamento de Ingeniería Textil y Papelera, Universitat Politècnica de València, Alcoy, Spain.

* Corresponding author: Miriam Martinez-Albert, Comfort Department, Textile Industry Research Association-AITEX, Alcoy, Spain. E-mail: mimartinezal@aitex.es

Abstract:
The thermal comfort of workers in outdoor environments is influenced by various factors, including environmental conditions, clothing choices, and the specific tasks being performed. Employees who work outside are at a higher risk of experiencing thermal stress in extreme weather conditions that are beyond their control. In situations with high temperatures and heat stress, personal cooling garments can be crucial for helping the body manage excess heat by reducing core and mean skin temperature. There are several types of cooling garments available on the market, and their effectiveness largely depends on the cooling mechanisms they utilise. The most common cooling mechanisms include air cooling garments, liquid cooling garments, evaporative cooling garments, phase change cooling garments, and hybrid cooling garments. Currently, a standard exists for assessing both the cooling power and cooling duration of these garments; however, there is no consensus in the literature on how these two factors affect user comfort. This study investigates the relationship between cooling power, cooling duration, and the working temperature of phase change material (PCM) cooling vests, focusing particularly on their melting point and how it influences the thermal sensation and comfort experienced by users. To facilitate this evaluation, we have used an innovative laboratory testing method that combines a thermal manikin with a computer simulation program designed to replicate the user's thermoregulatory system. The findings indicate a significant relationship between the melting temperature of the PCM cooling vest, its cooling duration, and cooling power, as well as their effects on the user's thermal sensation and comfort.

Keywords: Cooling vests, cooling garments, thermal comfort, personal cooling systems, thermal manikin.

1. INTRODUCTION

Personal cooling systems are designed to help users maintain thermal comfort during thermal stress by lowering internal body and skin temperatures and reducing sweat production. PCMs cooling vests are the most widely used and researched heat dissipation garments, owing to several advantageous attributes: their simple design, versatility due to varying melting points of the PCMs, effective short-term cooling capabilities, reusability, and the absence of a need for an electrical power source [1]. The cooling effect of these vests is based on microencapsulation technology. In this process, PCMs start in a solid state and, as temperatures rise, the microcapsules absorb energy until they reach their melting point, transitioning from solid to liquid, providing a cooling sensation

[2]. These PCMs can be integrated into vests by finishing fibres with PCMs or including PCM packages [3].

2. METHODS

2.1 Methodology

The characterisation of cooling vests is guided by the ASTM F2371-24 Standard Test Method for Measuring the Heat Removal Rate of Personal Cooling Systems (PCS) Using a Sweating Manikin [4]. Utilising a sweating manikin, this procedure measures both the heat removal rate and the duration of cooling. The sweating manikin from the company Thermetrics LLC. [5] can be paired with simulation software replicating a person's thermoregulatory system within the body of the thermal manikin. The Manikin PC Software was developed by the company Thermoanalytics Inc. [6] and integrates the thermophysiological prediction model created by Fiala et al. [7,8] along with the UC Berkeley Thermophysiological Comfort Model [9].

This study aims to assess two different phase change material (PCM) cooling vests with varying melting points using the established test protocol to evaluate the performance of cooling garments. The objective is to demonstrate how the melting point influences the physiological performance and thermal perception of the manikin wearing these PCM cooling vests. Previous laboratory studies have shown a robust correlation between the results obtained through the ASTM F2371-24 standard and those measured with a thermal manikin coupled with the Manikin PCM software, employing a testing protocol designed to evaluate the cooling performance of cooling vests [10].

2.2 Equipment

A thermal manikin with 34 segments is used with the Manikin PC Software. This manikin is made according to standard ISO 15831-04 [11] and ASTM F2370-24 [12].

During the tests, the thermal manikin is placed inside a climatic chamber of 14 meters in length, 3 meters in width, and 5 meters in height.

2.3 Experimental design

2.3.1 Test samples and conditioning

The study analyses the thermal comfort of two cooling vests with PCMs at melting temperatures of 21.0ºC and 29.0ºC. According to the manufacturer's instructions, PCM's cooling vests can be activated for 20 minutes in ice water, 40 minutes in the freezer, and 60 minutes in the refrigerator. In our study, testing vests are conditioned for 40 minutes in a freezer at -30.0 ºC before each test. These vests have been tested according to ASTM F2371-24 in a previous study [13]. Results of cooling capacity are presented in Table 1.

Table 1. Cooling capacity and cooling duration.

Cooling vest	Cooling power (W)	Cooling duration (min)
21ºC	183	38
29ºC	71	20

2.3.2 Test protocol

The manikin is placed inside a climatic chamber set to an ambient temperature of 35.0 ± 0.5 ºC, a relative humidity of 40 ± 5%, and an air speed of 0.4 ± 0.1 m/s. At the start of each test, the manikin is in a thermoneutral state that ensures the manikin is in the same neutral state before each test. Upon completion of the baseline assessment, the manikin is outfitted with different cooling vests and proceeds to simulate the activities. After the thermoneutral test, the only input needed for the software to start the test is the metabolic rate of a specific activity (METs). Three activity levels are used in the simulation, each for 20 minutes. This evaluation started with a low metabolic rate activity level (1.4 METs), continuing with a moderate metabolic rate activity level (2.8 METs) and finished with a high metabolic rate activity level (4.0 METs).
We will focus on measuring only the torso area of the manikin, as this is the specific region covered by the vest. For each activity level, the parameters considered in this study are: Overall skin temperature (T_{sk}), hypothalamus temperature (T_{hy}), thermal sensation index, and thermal comfort index. Thermal comfort is on the 7-point scale of 3 (very uncomfortable) to +3 (very comfortable). Thermal sensation is on a 7-point scale from -3 (very cold) to +3 (very hot).

3. RESULTS

Table 2 compares the manikin's overall skin temperature (T_{sk}), hypothalamus temperature (T_{hy}), thermal sensation index and thermal comfort index for the two different cooling vests tested.

Table 2. Results of the cooling vests tested.

Cooling vest	METs	T_{sk} (ºC)	T_{hy} (ºC)	Thermal comfort index	Thermal sensation index
21ºC	**1.4**	33.1	37.1	2 Comfortable	0 Neutral
	2.8	33.8	37.3	0 Neutral	0 Neutral
	4.0	35.0	37.6	-1 Slightly uncomfortable	1 Slightly hot
29ºC	**1.4**	34.4	37.3	1 Slightly comfortable	0 Neutral
	2.8	36.0	38.1	-1 Slightly uncomfortable	1 Slightly hot
	4.0	37.0	38.4	-1 Slightly uncomfortable	2 Slightly hot

4. DISCUSSION

The overall skin temperature measurements taken during various simulated activities show that the manikin wearing the PCM cooling vest of 21ºC has a lower skin temperature than the manikin wearing the PCM cooling vest of 29ºC. This observation aligns with the cooling capacities of the vests: the 21ºC PCM cooling vest, which has a higher cooling capacity, effectively maintains a cooler skin temperature compared to the

29ºC vest. A similar correlation is observed with the temperature of the hypothalamus. The thermal sensation is associated with the skin temperature and the hypothalamus temperature. In the case of the PCM cooling vest of 21ºC, we can see that at lowenergy and medium-energy activities, the thermal sensation of the manikin remains neutral. In contrast, in a high-energy activity, the thermal sensation of the manikin is slightly hot. For the manikin wearing the PCM cooling vest of 29ºC, only for a lowenergy activity, the sensation of the manikin is neutral, while at higher metabolic rate activities, it is worse, with a feeling of being slightly hot. Thermal comfort has a direct relationship between the skin temperature, the hypothalamus temperature and the thermal sensation of the manikin. For the PCM cooling vest of 21ºC, at low-energy and moderate-energy activities, the thermal comfort of the manikin is positive, being comfortable in a low-energy activity and neutral in a moderate-energy activity. Regarding the PCM cooling vest of 29ºC, only at low-energy activity, the thermal comfort is positive, with the manikin slightly comfortable.

5. CONCLUSION

Based on the results, using phase change materials (PCMs) with a melting point of 21ºC for cooling vests is highly recommended for low- to moderate-energy activities lasting around 40 minutes. In contrast, the PCM cooling vest with a melting point of 29ºC is only suitable for low metabolic energy activities, such as sitting or standing, and should be used for a short duration of up to 20 minutes. The study revealed a strong correlation between the standard ASTM F2371-24 and a testing method that uses a thermal manikin to evaluate the effects of cooling garments on thermophysiological parameters, user sensation, and comfort. The findings indicate a direct relationship between the melting point of the phase change materials (PCMs) used, their cooling capacity, the duration of cooling, and the users' thermal comfort and sensation. Specifically, PCMs with lower melting points provide higher cooling capacity, longer cooling duration, and improved thermal sensation and comfort. However, it is essential to avoid using PCMs with very low melting points, as they can pose a risk by excessively lowering the user's body temperature.

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Maximum Skin Wettedness While Wearing Woven and Non-Woven Clothing

Thomas E. Bernard[1], George Havenith[2], Candi D. Ashley[3]

[1]College of Public Health, University of South Florida, Tampa FL USA, Corresponding Author, tbernar2@usf.edu
[2]Environmental Ergonomics Research Centre, School of Design and Creative Arts, Loughborough University, Loughborough UK
[3]Exercise Science Program, College of Education, University of South Florida, Tampa FL USA

Keywords: sweat evaporation, evaporative efficiency, heat stress

Abstract

Introduction. Maximum skin wettedness (w_{max}) is the ratio of required evaporative cooling (E_{req}) divided by maximum evaporative cooling (E_{max}) at the upper limit of thermal equilibrium. In the semi-nude case, w_{max} has reported values between 0.2 and 1.0 depending on ambient water vapor pressure, acclimatization state, metabolic rate, fitness, and age. While w_{max} occurs at maximum rate of sweating at low evaporative resistance, this paper reports on w_{max} while wearing different clothing ensembles that cover most of the body.

Methods. A progressive heat stress protocol identified the critical environment at the upper limit of thermal equilibrium. The 445 observations included five clothing ensembles (shorts and tee shirt plus woven shirt and trousers, woven coveralls, nonwoven particle-barrier coveralls, nonwoven microporous water-barrier coveralls, and nonwoven vapor-barrier coveralls) at metabolic rates from 130 to 500 W and at three humidity levels (20, 50 and 70% RH). The resultant total insulation and resultant total evaporative resistance from manikin data were used to compute E_{req}, E_{max}, and w_{max}. A linear mixed model was fit to the 445 observations. Metabolic rate was a continuous variable, RH level and Ensembles were fixed effects, and participants were a random effect.

Results. w_{max} increased with metabolic rate. There was a difference among ensembles where w_{max} for vapor-barrier at 1.80 was higher than the other ensembles at 1.45. w_{max} changed across the three humidity levels, where 20% was 1.18, 50% was 1.59, and 70% was 1.78. There was no interaction between RH and Ensembles.

Conclusions. w_{max} increased with increasing metabolic rate, increasing ambient humidity, and for high evaporative resistance (i.e., vapor-barrier coveralls over the other woven and nonwoven ensembles). Importantly, w_{max} was consistently greater than 1, which means the skin was fully wetted for maximum surface coverage. While w_{max} represents a physiological limit in the seminude case, it represents additional distribution of sweat beyond the skin to the clothing and more complex pathways for overall cooling as well as loss of water due to dripping.

Introduction

Skin wettedness (w) was introduced by Candas et al. to describe a theoretical skin coverage of sweat (Candas et al., 1979a) as the ratio of sweat evaporation rate (SR_{evap}) over total sweat rate (SR_{total}). They reported a maximum skin wettedness of 0.7 for unacclimatized semi-nude participants and 1.0 for acclimatized participants (Candas et al., 1979b). They also noted that increasing skin wettedness resulted in lower cooling efficiency for the sweat loss (Candas et al., 1979b) due to dripping. This observation has led to a relation between wettedness and sweating efficiency; such as the one used in the PHS model (ISO, 2023). In the context of thermal comfort, Havenith et al. pointed out that skin wettedness will increase with the evaporative resistance of clothing and metabolic rate (Havenith et al., 2002).

Recently, a partial calorimetry method to estimate required skin wettedness (w_{req}) was presented as a ratio of required evaporative cooling (E_{req}) to maximum evaporative cooling (E_{max}) (Cramer & Jay, 2018; Lynch et al., 2024). At the upper limit of thermal equilibrium, maximum skin wettedness (w_{max}) is reached, and $w_{max} = E_{req}/E_{max}$ (Cramer & Jay, 2018). In the semi-nude case, w_{max} has reported values between 0.2 and 1.0 depending on ambient water vapor pressure, metabolic rate, fitness, age (Fisher et al., 2025; Fisher et al., 2024), and acclimatization state (Lynch et al., 2024).

With low evaporative resistance (e.g., shorts and shoes with or without tee shirt), w_{max} (using the E_{req} to E_{max} definition) occurs at maximum rate of sweating, a physiological limit to evaporative cooling. Similar to w based on sweat rates, as wettedness increases (e.g. due to increasing E_{req} or decreasing E_{max} at higher water vapor pressure), there is a dripping of sweat off the body as w approaches or exceeds 1. The underlying assumptions are that w and w_{max} are the same under similar conditions and that the efficiency relations are also the same.

The PHS model for heat stress uses the sweating efficiency relation to back calculate required sweat rate from E_{req} (ISO, 2023). The model considers clothing only in determining E_{max}, and does not consider clothing further in the back calculation of SR_{req}.
Sweating efficiency approaches 0.05 as w_{req} approaches 2.0.

This paper reports on w_{max} using the partial calorimetry method (Cramer & Jay, 2018) while wearing different clothing ensembles with different levels of evaporative resistance.

Methods

Participants in this study signed an informed consent and were qualified healthy by a physician. A progressive heat stress protocol identified the critical environment at the upper limit of thermal equilibrium (Bernard et al., 2024). The 445 observations included five clothing ensembles (shorts and tee shirt plus woven shirt and trousers, woven coveralls, nonwoven particle-barrier coveralls, nonwoven microporous water-barrier coveralls, and nonwoven vapor-barrier coveralls) at metabolic rates from 130 to 500 W
(Low, Moderate, High) at 50% relative humidity (Bernard et al., 2008) and at three humidity levels (20, 50 and 70% RH) at a metabolic rate of about 300 W (Bernard et al., 2005).

The resultant total insulation ($I_{c,T,r}$) and resultant total evaporative resistance ($R_{e,T,r}$) were determined from existing manikin data adjusted according to ISO9920 (ISO, 2007), equations 32 and 38, respectively, for the individual test conditions (Caravello et al.,
2008). $I_{c,T,r}$ and $R_{e,T,r}$ were used to compute E_{req}, E_{max}, (Caravello et al., 2008) and w_{max} (Lynch et al., 2024) at the upper limit of thermal equilibrium.

$$E_{req} = (M - W) + (C + E)_{res} - S + (T_{db} - T_{sk})/I_{c,T,r} \quad 1$$

$$E_{max} = - (P_{sk} - P_a)/R_{e,T,r} \quad 2$$

$w_{max} = E_{req} / E_{max}$

First, an analysis of variance was run on the categorical variables of ensemble (5 levels), metabolic rate (3 levels), and relative humidity (3 levels) plus the interaction of ensembles and relative humidity. Then a linear model was fit to the 445 observations.
w_{max} was the dependent variable. Metabolic rate, $R_{e,T,r}$, and ambient water vapor pressure (P_a) were continuous variables, and participants was a random effect.

Results

Based on the ANOVA, w_{max} increased with metabolic rate. There was a difference among ensembles where w_{max} for vapor-barrier at 1.80 was higher than the other ensembles at 1.45. w_{max} increased across the three humidity levels, where 20% was 1.18, 50% was 1.59, and 70% was 1.78. There was no interaction between relative humidity and ensembles.

The multiple linear regression yielded Equation 4 with statistically significant terms. When the mean values of 168 W/m^2 for M, 3.1 kPa for P_a, and 0.0275 m^2 kPa/W for $R_{e,T,r}$ are , w_{max} was 1.55.

$$w_{max} = -1.13 + 0.00496\, M\, (W/m^2) + 0.392\, P_a\, (kPa) + 22.9\, R_{e,T,r}\, (m^2\, kPa/W) \quad 4$$

Discussion

As to be expected, w_{max} increased with increasing metabolic rate and ambient water vapor pressure. These relations were shown by others for partial clothing coverage (Fisher et al., 2025; Fisher et al., 2024; Lynch et al., 2024). This study extends that observation for woven and nonwoven coveralls.

The previous studies reported on light clothing (shorts and shoes with or without a tee shirt) with low total evaporative resistance, much of it associated with the air layer. Adding coveralls adds substantially to $R_{e,T,r}$. The mean value was 0.0275 m^2 kPa/W compared to 0.017 (Fisher et al., 2025) and 0.003 (Lynch et al., 2024). This then asks the question of what's the meaning of w_{max} for values greater than 1.0.

With clothing, dripping water is not necessarily lost to the cooling function. It wets the clothes (thereby expanding wet surface area) and allows evaporative cooling of the clothing, which in turn can cool the person. Interestingly, E_{req} was not significantly related to w_{max}. On the other hand, E_{max} was significantly and negatively related to w_{max}. That is, increases in skin wettedness were easily attributed to a decreasing denominator, E_{max}, rather than changes to E_{req}. Intuitively, decreasing E_{max} means more sweat is available to wet the clothing and thus allow for indirect cooling of the body. It is not clear that the sweating efficiency developed for freely evaporating sweat from skin can be extrapolated to clothed conditions.

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Conflicts of Interest

The authors have no conflicts of interest to declare.

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Evaluation of Heat Stress Prediction for Structural Internal Firefighting Scenario

Klomp, A.M.H.[1], Jacobs, L.M.G.[1], Daanen, H.A.M.[1], Kuklane, K.* [2,3]

[1] Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

[2] Team Fire Service Science, Netherlands Academy of Crisis Management and Fire Service Science, Netherlands Institute for Public Safety (NIPV), Arnhem, The Netherlands

[3] Chair of Biosystems Engineering, Institute of Forestry and Engineering, Estonian University of Life Sciences, Tartu, Estonia

* Corresponding author: kalev.kuklane@nipv.nl

ABSTRACT

Firefighters face hazardous conditions that can induce negative physiological and psychological responses, more specifically heat strain. The Predicted Heat Strain model (PHS, ISO7933) enables the determination of heat strain while considering clothing properties, environment and activity in predictive calculations. However, PHS was originally developed for industrial applications. For suggesting potential adjustments in ISO 7933 for firefighter work, this study aimed to evaluate PHS algorithms for firefighters under simulated structural interior firefighting activities (SIF).

Four firefighters wearing turnout gear performed pre-work and recovery at room temperature, and intermittent activities in a climate-controlled room (T_a = 44.4 ± 0.2 °C, RH = 27.8 ± 1.6 %, v_a < 0.15 m/s). Clothing thermal insulation and evaporative resistance were determined using a thermal manikin. Skin (T_{sk}) and rectal temperatures (T_{rec}), and body water loss (m_{wl}) were compared with PHS predictions using two online tools that allow input of intermittent conditions – FAME Lab (PHSFL) and the Lund University modified PHS (PHSLU).

Experimental T_{rec} did not differ significantly from the PHSLU predictions. For PHSFL, T_{rec} became significantly lower at the end of heat exposure and during recovery. Experimental T_{sk} was initially lower than predicted by PHSFL. Predicted T_{sk} decreased more rapidly than measured values at the end of radiation period for PHSLU, while reduction in PHSFL occurred slightly later. Both models predicted T_{sk} values that were lower than the experimental data throughout the recovery period. Overall the PHS models gave reasonably accurate predictions for both T_{rec} and T_{sk} in this scenario (RMSD < SD), but m_{wl} (> 1000 g) exceeded significantly measured one (630 ± 209 g).

The models may not adequately account for thermal inertia of the clothing system and/or heat distribution within it. Considering other scenarios and existing literature, it is clear that the PHS model requires adjustments for realistic predictions under firefighter conditions. Further detailed analysis is needed to determine the necessary modifications.

Keywords: *firefighter, protective clothing, predicted heat strain, heat stress, physiological responses*

1. INTRODUCTION

Firefighters often perform heavy work in high ambient temperatures. Heat flux from flames, heat radiation, and dangerous situations impact negatively both their health and safety (Fullagar et al., 2021; Sandsund et al., 2024). Lee et al. (2017) reported that about half of the firefighters encountered significant hazards during operational tasks. Under these conditions firefighters perform high intensity work and thermal energy is transferred to the skin through radiation, conduction, and convection (Lei et al., 2023).

Heavy and semi-permeable protective clothing is commonly used for protection against these hazards (Holmér et al., 2006; Rathour et al., 2021). Increased protection elevates the bulk and carried weight which reduces physical performance, increases metabolic load and raises internal body heat production (Dorman, 2007; Dorman & Havenith, 2009; Teitlebaum & Goldman, 1972). Significant levels of heat stress develop quickly during hot, high-intensity activities when wearing heavy clothing, leading to adverse physiological and psychological responses, known as heat strain, and to heat-related disorders (Moran et al., 2003; Petruzzello et al., 2009). Physiological responses, including increased skin and core temperature may lead to an enhanced risk of heat-related injuries (Carballo-Leyenda et al., 2022; Eggenberger et al., 2018; Færevik & Reinertsen, 2003; Renberg et al., 2022). Reduced mobility, flexibility, and dexterity may also restrict the ability to successfully accomplish a task (Aljaroudi et al., 2022; Son et al., 2022; Tochihara et al., 2005; Wang et al., 2021).

To investigate the effect of clothing on human thermal comfort and thermal stress across various environments, clothing thermal insulation and evaporative resistance should be considered when planning activities, organizing work and selecting optimal protection (Xu et al., 2014). For that purpose various thermo-physiological prediction models are available (Havenith & Fiala, 2016). One of these is easily available as a standard on Predicted Heat Strain (PHS, ISO

7933; Malchaire et al., 2001). However, PHS has been developed mainly for industrial work, and may not accurately predict outcomes outside its validity range (Wang et al., 2013). For advising adjustments of ISO 7933, the objectives of this study were to evaluate PHS algorithms for firefighters during simulated rescue scenarios. This work validates PHS for structural interior firefighting (SIF) under intermittent conditions.

2. MATERIALS AND METHODS

2.1. PHS

Predicted heat strain (PHS, ISO 7933) utilizes clothing properties, environmental parameters and activity levels in calculations. Two online tools allow input of intermittent conditions for PHS calculations: a version from FAME Lab (PHSFL, https://habitatscience.org/famelabphs.html based on an ISO 7933 version under revision from 2018) and a Lund University modified PHS version (PHSLU, https://github.com/Rikuklane/PredictedHeatStrainModel based on ISO 7933:2004). These tools were utilized on a dataset collected during extensive testing on professional firefighters under simulated rescue scenarios and various clothing combinations (Kuklane et al., 2024b; Kuklane et al., 2025; Levels et al., 2024). As the PHSFL version did not allow entering enough timesteps for accounting in all intermittent parameters, intermittent IR radiation was timeweighed in both models. The mean power over the period of intermittent high radiation was used to calculate the mean radiant temperature input for the model following Gebhardt et al.
(1995) and Annex B of ISO 7726:1998.

2.2. Test persons and clothing

For the PHS evaluation in the SIF scenario, data from four (4) test persons (TP) wearing traditional Dutch turnout gear system were used. On average, TP had an age 39 ± 14 years, a body mass of 86.0 ± 18.3 kg, a height of 1.87 ± 0.05 m, a body area of 2.10 ± 0.22 m^2, and a body fat of 20.6 ± 7.2 %. None of TP was smoking and all were in active duty. Used basic clothing insulation (I_{cl}) were 2.17, 2.39 and 1.12 clo, clothing evaporative resistance (R_{ecl}) 74.2, 78.7 and 33.0 m^{2}Pa/W, and clothing moisture permeability index ($i_{m,cl}$) 0.25, 0.27 and 0.32 for pre-work, heat exposure and recovery, respectively (Kuklane et al., 2024a). The areas covered by reflective tapes were taken equal to 0.22 m^2 corresponding to coverage of 8.2 % during prework, 7.4 % during heat exposure (SCBA bottles worn on top), and 3.9 % during recovery period (no jacket). Emissivity of the reflective tapes was assumed to match oxidized aluminium, (0.20). Skin (T_{sk}) and rectal temperatures (T_{rec}), and body water loss (m_{wl}) of the human tests were compared with PHS predictions. Each TP was modelled separately and then the averages and the standard deviations (SD) were calculated for each parameter.

2.3. Environment and activity levels

Test person preparation, pre-work and recovery were performed outside the test room at air temperature (T_a) of 17.8 ± 1.4 °C, relative humidity (RH) of 56.0 ± 7 %, and air velocity (v_a) of less than 0.15 m/s, and exercise in heat in a climate controlled room at T_a = 44.4 ± 1.0 °C, RH = 30.0 ± 9.5 %, v_a < 0.15 m/s. The activities during SIF simulation were bicycling at 50 W (0-18 min, pre-work), donning the bottles and entering the climate controlled room (18-20 min), walking at 3.1 km/h (20-30 min), walking at 4 km/h with added intermittent IRradiation of 4 kW/m^2 from right side (on/off each minute, 30-35 min), continue walking at 5.4 km/h with the intermittent IR-radiation (35-40 min), walking at 4 km/h without IR-radiation (40-45 min), walking at 5.4 km/h without IR-radiation (45-50 min), and recovery period with seated rest (50-80 min). The measured average metabolic rates for these activities were 193 ± 7, 174 ± 9, 194 ± 13, 257 ± 20, 203 ± 27, 259 ± 33 and 68 ± 7 W/m^2, respectively. The mean radiation temperature during the pre-work and recovery was set equal to room temperature (17.8 °C), during activities without radiation to climate room temperature (44.4 °C), and on average 63.3 °C during the period with intermittent IR-radiation.

3. RESULTS AND DISCUSSION

Figure 1 shows the mean skin temperature (T_{sk}) and Figure 2 shows average rectal temperature (T_{rec}) development during the experiment and the model predictions. Asterisks (*) indicate experimental periods with significant differences between the experimental data and the models. Figure 3 shows a comparison of cumulative body water loss (m_{wl}).

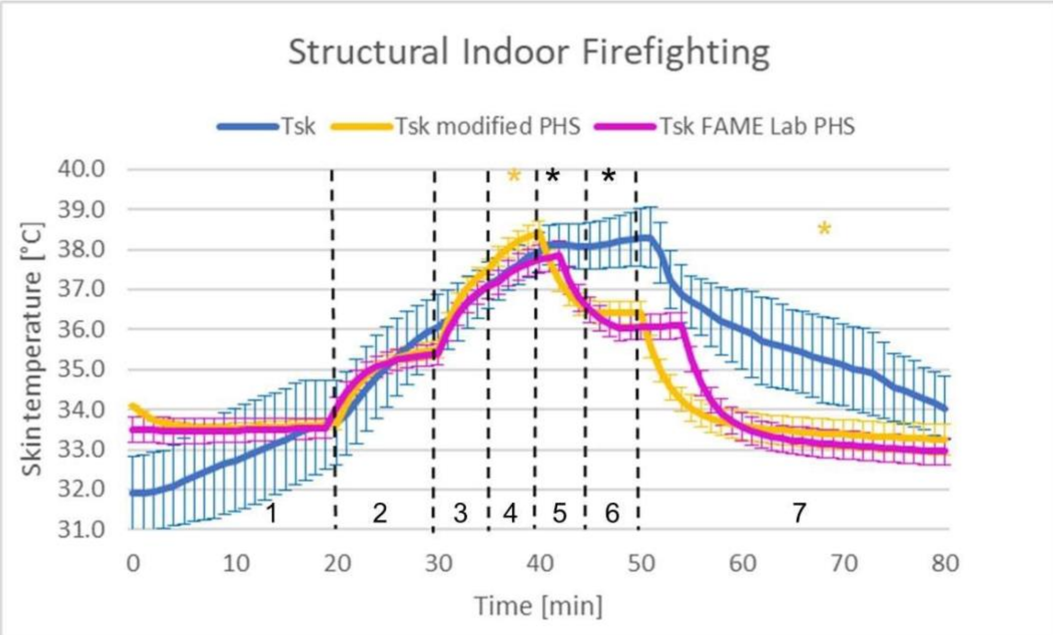

Figure 1. Skin temperatures during experiment and model predictions. * shows significant difference between experimental data and model outputs within study stages (1-7). Black * denotes differences in both models, while coloured * denotes difference in T_{sk} for the respective model only.

SD of m_{wl} was approximately 200 g in all cases. Significant differences were observed between modelled and measured data, with modelled m_{wl} generally about 400 g higher than experimental values (Figure 3). T_{sk} was initially lower in the experimental data than in the model output (Figure 1). However, the reaction to environmental change or change in radiation impacted T_{sk} much more abruptly than in the experiment. Additionally, PHSFL showed an increasing delay in reactions over time, particularly at the start of recovery, and where experimental T_{sk} began to decrease shortly after jacket removal.

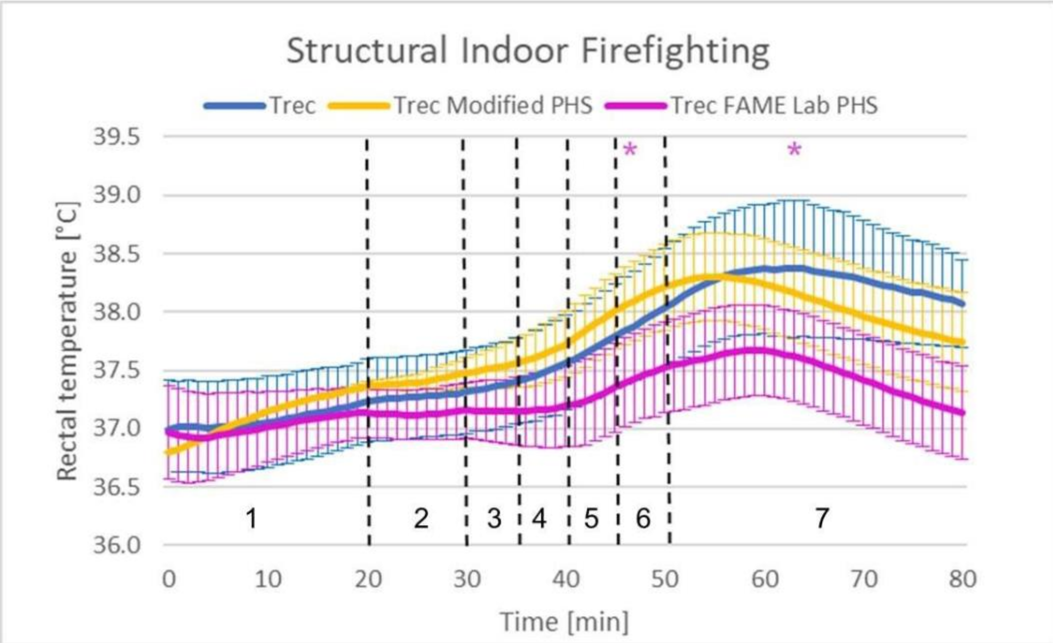

Figure 2. Rectal temperatures during experiment and model predictions. * shows significant differences between experimental data and model outputs within study stages (1-7). Black * denotes differences in both models, while coloured * denotes differences in the respective model only.

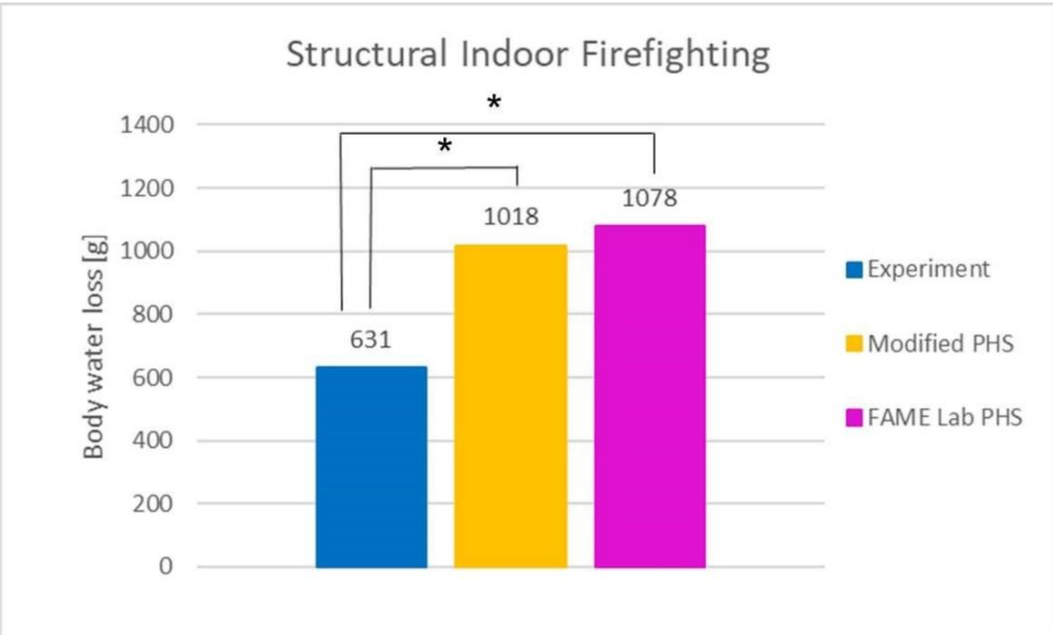

Figure 3. Body water loss. * shows significant differences

Although initially higher, modelled T_{sk} commonly remained below experimental values. This is likely due to higher modelled m_{wl} (sweating, Figure 3), and the resulting higher expected evaporative cooling in the models, which lowered T_{sk} relative to the measured values (Figure 1). Another important observation is that T_{sk} in the models reacted very quickly to changes in radiation load. This may reflect model assumptions corresponding to relatively light clothing or nude skin, rather than the heavy, high insulation protective gear used in the experiments. Model calculations include insulation, but they appear not to fully account for the evaporative resistance and thermal mass/inertia of the clothing system. PHSFL had no evaporative resistance-related input, and likely defaults to normal clothing values (i_m=0.38) by default, whereas PHSLU uses measured moisture permeability index (i_m). This likely explains somewhat higher T_{sk} (Figure 1) and T_{rec} (Figure 2) for PHSLU than for PHSFL, as PHSLU utilizes the actually measured, considerably lower i_m values. Simultaneously, T_{rec} of PHSLU did not differ significantly from the experimental values, while differences with PHSFL gradually increased, becoming significant by the end of the heat exposure and recovery in SIF. For a valid prediction, the root mean square deviation (RMSD) should be smaller than the SD. In the case of SIF, RMSD for T_{rec} was 0.19 and 0.52 for PHSLU and PHSFL, respectively, vs. experimental SD of 0.41. RMSD for T_{sk} was 1.49 and 1.41 for PHSLU and PHSFL, respectively, vs. experimental SD of 1.95. This indicates that PHSLU provided valid predictions for exposure under SIF scenario, while PHSFL did not. Considering that firefighters T_{rec} may reach or exceed 39 °C (with generally accepted occupational exposure limits around 38-38.2 °C), the generally accepted prediction accuracy of 0.5 °C is insufficient for firefighter exposures and we should aim for a target accuracy of 0.2 °C.

This study and the related ones in different conditions, e.g. technical rescue in warm weather (TRW, Klomp et al., 2024), wildland firefighting (WLF, Jacobs et al., 2024), and other PHS model validation studies (Kuldmäe et al., 2025; Lundgren et al., 2017; Wang et al., 2013) show varying grade of match. Thus, the PHS model needs to be adjusted for use in more extreme conditions than its validity range.

Taking additionally into account wide individual differences (Notley et al., 2025) then direct measurements of critical physiological parameters is to be preferred. High individual variation of TP data suggests also that any devices relying on models or empirical relationships have to allow for individual calibration. Such individual model calibration parameters, in addition to body size, can be personal resting and maximal heart rates. For firefighters this data should not be impossible to acquire as they must pass regular medical and fitness checks.

4. CONCLUSION

Considering the results of this comparison, as well as the findings from related model validation studies, neither PHS tool gave a reasonably good and reliable prediction. In some cases, the differences between modelled and measured data were significant, while in others they were not. Consequently, the current PHS models cannot be reliably used to predict firefighter exposures or those of other occupations requiring highly protective clothing. However, the study highlights several factors that must be considered when attempting to apply the model outside its present validity range. These include incorporating evaporative resistance or the clothing permeability index, and accounting for the mass and thermo-physical properties of the protective clothing materials and equipment system.

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