ABSTRACT

GODOWN, RACHEL ELIZABETH. Assessing the Effectiveness of Clothing Ventilation Designs in Men's Business Wear for Improved Comfort Performance. (Under the direction of Dr. Katherine Annett-Hitchcock).

The purpose of this research was to explore the impact on human thermal comfort that new ventilation design features could have for men's business wear, specifically men's dress shirts. Ventilation features and technology have long been integrated into athletic apparel, outdoor wear, and protective clothing with the goal to improve the wearer's comfort and performance, but this area has not been well studied in business apparel.

In this study, three fabrics were selected for inclusion in initial physical testing: a control fabric of 100% woven cotton; a woven TransDRY® fabric (100% treated cotton) with the multiple ventilated designs; and a knit X-TEMP® fabric (90% cotton / 10% polyester). These fabric samples were tested for thickness and air permeability measurements. Based on the measurements obtained during this initial phase, one specific ventilation design was selected for implementation into a prototype men's dress shirt using the TransDRY® woven fabric.

In the second phase of the study, garment level testing using a sweating manikin was performed to determine how the ventilated prototype dress shirt would perform compared to a 100% woven cotton control shirt and a knit polo shirt made from X-TEMP® fabric. Measurements were taken in both static (standing) and dynamic (walking) conditions to simulate typical office environment situations. Data calculations were made for predicted total heat loss for each shirt configuration. Results of the tests showed that the ventilated business dress shirt was equal to or slightly better than the performance of the knit polo shirt in predicted total heat loss.

The study's findings indicate that a combination of ventilation design features and fabric technology could provide the most promising results to address the need for more comfortable and cooler men's business dress shirts.

Assessing the Effectiveness of Clothing Ventilation Designs in Men's Business Wear for Improved Comfort Performance

by
Rachel Elizabeth Godown

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Textiles

Raleigh, North Carolina

2017

APPROVED BY:

Dr. Katherine Annett-Hitchcock Chair of Advisory Committee	Dr. Emiel A. DenHartog
Dr. Andre West	Dr. Meredith L. McQuerry External Committee Member

DEDICATION

This thesis is dedicated to my mom and dad. Without your constant support and encouragement this achievement would not have been possible. Thank you for all you have done to help me reach for the stars.

BIOGRAPHY

Rachel Elizabeth Godown was born on March 10, 1993 in Johnson City, New York; and grew up in Raleigh, North Carolina, the youngest daughter of Terence Carl Godown and Suzanne Carroll Godown, and sister to Katherine Anne Thompson. After graduating from Leesville Road High School in the spring of 2012, Rachel began her education at North Carolina State University. Rachel graduated from the College of Textiles at North Carolina State University with a Bachelor of Science in Fashion and Textile Design with a concentration in Fashion Design in the spring of 2016. During her time as an undergraduate at North Carolina State University, Rachel was a member of Kappa Delta Sorority and a member of Phi Psi National Textiles Fraternity.

ACKNOWLEDGEMENTS

There are several people who without their help and support this thesis would not have been possible. I want to thank the following people:

Dr. Katherine Annett-Hitchcock, my committee chair, for your support and counsel through this process. Your commitment, enthusiasm and patience helped make this idea a reality.

Dr. Andre West, **Dr. Emiel DenHartog** and **Dr. Meredith McQuerry**, the remaining members of my committee, for serving on this committee, your advice and help that has made this research possible.

A huge thank you to **Hanesbrands Inc.** and **Keith Zimmerman** for their financial support of this endeavor. Thank you for your backing of my academic pursuits.

Cotton Incorporated and **David Earley**, for your interest in this project from the beginning and your generous fabric donations, this project would not have been possible without you.

My amazing **family** and **friends,** without you I would be truly lost, your unending support and encouragement has kept me sane. I could not have done this without you. Thank you for your belief in me.

Kyle Watson and the **TPACC Laboratory**, without you to run the Sweating Manikin tests and then explain the results in the simplest of terms, I would not have survived.

Teresa White and the **Physical Testing Laboratory**, for allowing me to use the lab, showing me how to use the equipment and always answering my questions.

Dr. Traci Lamar, for your help with my laser cutter authorization and allowing me to use the laser cutter for this project.

Robert Cooper, for your help with all the paperwork and forms needed to make this all possible.

Finally, to the remaining faculty and staff of the **College of Textiles** for all you have taught me to become the designer I am today. This would not have been possible without you.

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INTRODUCTION

Much of the research into clothing thermal comfort focuses on functional aspects of clothing, such as, sports apparel, outdoor clothing, and protective clothing. There is a need and commercial market for increased thermal comfort in men's business wear for the work environment. This research was designed to focus on men's business shirts, which are integral to the business "uniform", and to investigate new design features to incorporate both functional and aesthetic attributes. For retail application, shirts need to be wearable, visually appealing, and commercially viable. The goal of this research was to determine whether a new design incorporated into a woven business dress shirt provided comparable thermal comfort to a knitted polo shirt already commercially available.

Significance of Study

Recent Environmental Protection Agency (EPA) guidelines in the United States have called for improved human thermal comfort in indoor office spaces (Mendell & Mirer, 2009). It was with these guidelines in mind that the topic of ventilation in clothing was chosen for its relevance to the clothing industry and its application in a business environment. As stated by Dukes-Dobos, Reischl, Buller, Thomas and Bernard (1992), ventilation is defined as, "the amount of ambient air that flows under the garment after passing through the fabric and/or through (designed) openings." Since the focus of the EPA guidelines is on indoor office spaces, the focus of this study was on business wear, specifically men's dress shirts. This research goes beyond achieving a physically comfortable garment design. It is about providing consumers with an increased sense of confidence when wearing business wear by improving breathability through clothing ventilation and, therefore, improving thermal comfort in the workplace. Instilling a greater sense of self-assurance allows employees to perform at their best instead of being concerned about extremes in temperature and how their bodies might respond in the workplace (Ward, 2008).

Research Objectives

The objectives of this research were:

1. To determine whether men's business clothing can be redesigned for improved thermal comfort
2. To formulate a design for increased ventilation that is appropriate for an office environment
3. To achieve measurable heat loss and enhanced thermal comfort of the wearer as compared to a knitted polo currently on the market

Research Tasks

1. Identify ventilation designs currently implemented in a wide variety of apparel products.
2. Down-select appropriate ventilation features to incorporate into men's business wear for improved heat loss and thermal comfort.
3. Assess the selected ventilation features to determine how they affect the functionality of the garments through fabric physical testing.
4. Design and fabricate a men's dress shirt which incorporates new, original ventilation features based on ventilation research.
5. Test and compare the ventilated woven garment; with a woven control shirt; and a knitted polo currently in the market; to determine if a ventilated woven dress shirt can be a suitable alternative for increased thermal comfort in the workplace.

Research Design

This study followed a mixed methods research approach, utilizing both qualitative and quantitative research applying the sequential exploratory design type (Creswell, J., Plano Clark, V., Gutmann, N., & Hanson, W., 2003). While the topic of ventilation and human thermal comfort has been studied extensively in performance sportswear, applying ventilation design features to men's business wear, specifically dress shirts, has not been explored. It is for this reason that following a mixed methods research design helped to facilitate the research's overall direction, procedures, and efficiency.

LITERATURE REVIEW

Clothing thermal comfort research and practice spans a number of applications, including: sports, outdoor, military, chemical, and firefighter protection. Given the diversity of different applications that require attention to thermal comfort, this research focused specifically on reviewing the important findings in the area of ventilation research on clothing in less activity-specific contexts. The common perspective across ventilation studies reviewed focuses on the wearer's experience, emphasizing the importance of keeping the microclimate comfortable and the body at an appropriate temperature. Ventilation of the body can be achieved in the following ways: understanding and utilizing the mechanics of the human body in motion; using technological advancements in fabric; incorporating innovations in ventilation design features and placement; and hybrids of all three. This literature review will address all approaches.

Business Wear Design Concepts

For the purposes of this study, men's business wear is defined as what men wear to work in an office environment. It commonly includes a tailored suit, crisp dress shirt (usually in a neutral color) and a tie. (Weldon, 2000).

In recent years, there has been a trend toward two types of business wear. The men's business professional wear, as described above, consisting of: a two-piece suit with matching pants and jacket in neutral dark shades such as black or navy; a woven dress shirt with a collar, in neutral or white; and a tie, in an understated stripe or pattern. The second type of men's business wear is business casual. While professional, this style is not formal. The ensemble usually consists of a coordinating, but not matching, jacket and pants such as a blue blazer with khaki pants. The shirt may be a button-down, oxford cloth, a woven shirt with no color or a small mandarin collar or a knit polo. The shirt can vary in color and pattern. A tie is not worn with this style (Solnina, 2017).

What is considered acceptable for the business environment is also influenced by culture, environment, occupation and gender. While business casual is acceptable in many companies, men's business wear is trending back to a more formal, defined standard (Solnina, 2017). Business appropriateness guidelines remain somewhat subjective. A men's dress shirt that is thin and open, showing the wearer's skin through the shirt, would not be considered appropriate for a business environment. The determination of how thin, and how open must be balanced with the need for the garment to be suitable in a business environment and be appropriate for that environment.

Another key design concept used in this study was that of aesthetics. Aesthetics refers to the exploration into the nature of art, beauty, and taste which appeals to the senses. Applied in this study, aesthetics is the subjective evaluation criteria applied to the shirts being tested. It was applied with respect to how the ventilation features appeared in the garment and if they would be considered appropriate (Eckman & Wagner, 1995).

Thermoregulation and Heat Loss

Humans have the ability to maintain a relatively constant body temperature, regardless of the changes in external environmental temperatures. Thermoregulation or temperature regulation in humans is the balance between the amount of heat produced by the body and the amount of heat lost from the body in order to maintain a constant body temperature (Bouskill, Havenith, Kuklane, Parsons, & Withey, 2002; McQuerry, DenHartog, & Barker, 2016; Watkins 1984). Heat flows from higher temperatures to lower temperatures. An example of this is that when the body sits on the cold ground, the body loses heat to the ground. This heat transfer which occurs when two objects are in direct contact is called conduction. The transfer of heat by the movement of air or liquid moving past the body is called convection. When air is trapped inside a layer of clothing, the heat produced by the body warms that air; and as that same air flows over the skin it cools the body, allowing the clothing to assist in the process of thermoregulation.

When evaluating the effects that clothing has on body heat loss, there are two areas that must be considered. The '*microenvironment*' which is the immediate air layer outside the clothing ensemble and the '*microclimate*' which is the air layer between the clothing and skin. When the body experiences high microclimate temperatures, its primary mechanism to reduce excess heat and return to a constant temperature is through sweat evaporation. As the body sweats, and if clothing is worn, then the microclimate increases in humidity. If the clothing being worn also restricts the air movement within the microclimate, then the heat the body produced cannot be dissipated to the outside environment. Clothing characteristics like fit (loosely fitting or tight fitting); fabric type; and air permeability have an impact on how much sweat evaporation takes place.

Ventilation through Movement

When a body is in motion, heat is generated. As the body works harder many of the body's systems are affected: the heart beats faster; blood circulation increases as the blood vessels dilate sending more blood to the muscles and lungs; overall body temperature rises; and respiration and perspiration rates increase. Movement of the body also increases air circulation through clothing layers, known as the "bellows" ventilation effect, where the microenvironment surrounding the body is "pumped" through clothing layers as a result of the body's rhythmical movement of the arms and legs during physical activity. The body movement forces air through the traditional openings of collar, cuff or hem, as well as, designed openings such as vents, zippers or mesh panels. The clothing's microclimate air movement and air exchange are increased due to the extra air volume and movement.

Ventilation features and designs can change the thermal properties of the clothing (Bouskill et al., 2002; Vokac, Kopke & Keul, 1973). Openings at the cuffs and neck, as well as, any added ventilation features such as grommets under the arms, zippers or mesh are all examples of ventilation features which would allow air exchange. In addition, clothing fit also has an effect on the microclimate. Loose fitting clothing allows for more air pockets to exist within the microclimate of the clothing providing a greater potential for air and moisture exchange and escape through the garment's inherent and designed openings. For "bellows" ventilation to be most effective, loosely-fitted or semi-fitted clothing with suitable openings should be utilized to transport moisture-laden air out of the microclimate and allow sweat evaporation to take place (Watkins, 1984). The "bellows" effect optimizes the ventilation design features as well as the fabric's air permeability attributes for increased comfort and heat loss but is only effective when the body is in motion. A recent trend in office equipment is the treadmill desk, which may offer workers an opportunity to be more active as they work. This could allow them to experience some benefit of the "bellows" effect while they work. However, it is more likely that the majority of office workers are sedentary, where they may spend hours of their day at their desk or in meetings. For them, this research could provide a viable option to improved thermal comfort while maintaining normal business wear.

Technical Advances in Fabric and Materials

Hsu et al. (2016) investigated the use of nanoporous polyethylene (nanoPE) fabric as a material that promotes key attributes of cooling such as increased air permeability and water wicking capabilities. Through various tests, in comparison to cotton, two nanoPE cloths (one regular and one processed with polydopamine (PDA)) were tested using a device to simulate skin temperature. The PDA nanoPE sample was the most effective for personal thermal management because the polydopamine coating allows water to pass more easily through the nanoPE fabric allowing sweat to evaporate more quickly. Testing results indicated that the skin temperatures when covered with the processed nanoPE fabric were nearly 5^{o} F cooler than when covered with the cotton fabric.

The outdoor garment market has exhibited considerable interest in the development of modern waterproof fabrics which can provide maximum thermophysiological comfort. Ruckman, Murray & Choi (1999) evaluated the thermophysiological comfort of outdoor garments made from two types of fabrics - Polytetrafluoroethylene (PTFE) laminated fabric and polyurethane coated fabric; and three ventilation design features - pit zippers, venting pockets, and venting back. Evaluations were made during active and resting periods. Research results showed that the added design features dissipated body heat through ventilation and lowered skin temperature during exercise. In addition, the study showed that not only the inclusion of these features, but also their placement on the garment, improved the thermophysiological comfort of the wearer. At rest, it was the technical advancements in breathable fabric that played the more important role in body cooling. It is through the combination of design and technology that optimal thermal comfort can be achieved.

Numerous scientific advancements have resulted from the research conducted to support the National Aeronautics and Space Administration (NASA) space program. NASA has been interested in developing materials which would keep astronauts comfortable and cool and protect them from the extreme temperatures of space. NASA (2009), after initially utilizing liquid-cooled garments, moved on to fabric which could control temperatures without pumping liquid. Phase change materials (PCMs) were developed which change their physical state at different temperatures; much like a wax candle which when heated is liquid but when cooled is a solid. These materials store, release or absorb heat as they change their state from solid to liquid form; giving off heat as they go to a solid state, and absorbing heat as they move back to a liquid state (Phase Change Materials, 2004). Initial commercial applications and research into PCMs began in 1987 when Gateway Technologies, later named Outlast Technologies Inc., obtained the patent rights to incorporate microencapsulated phase change materials (mPCMs) into their commercial fibers and fabrics. Outlast Technologies produced consumer goods which utilized the temperature control in applications such as consumer beddings, medical supplies, and active and outdoor gear and apparel (NASA, 2009).

It is much more efficient, from a cost and energy perspective, to regulate the personal microclimate of an individual than it is to regulate an entire building's environment. A person's microclimate is directly related to clothing; therefore, researchers are studying how clothing fabrics can be utilized for temperature control in office environments. Gao, Kuklane, Wang and Holmer (2012) extended the research of phase change materials (PCM) into applications of wearable personal cooling. The study investigated whether personal cooling using phase change materials would improve thermal comfort in non-air conditioned office environments at 34^{o}C/93.2^{o}F as might be experienced in European countries during a heat wave or regularly in Asian countries (Gao et al., 2012). The study was specifically designed for office workers without outer protective clothing and whose activity level was low (less than 100 W/m^{2} – watts per square meter). The study tested a PCM cooling vest on a thermal manikin, as well as on eight male subjects in a simulated office environment with consistent temperatures. The key findings from this study indicated that the PCM cooling vest could reduce the torso skin temperature by 2-3^{o}C in a simulated office environment of 34^{o}C. Gao et al. (2012) concluded that the personal cooling measures using PCMs, was not only an effective and efficient personal cooling device in a non-air conditioned office environment but the PCM cooling vest could also be an alternative cooling method for vulnerable groups, such as the elderly or chronically ill, in areas where a heat wave could put these groups, who cannot regulate their own body temperature, at risk.

Innovations in Design Features and Placement

Ventilation design features can be added to clothing in order to provide relief from overheating. Much of this research has focused on the reduction of wearer discomfort in professions where protection from the environment is necessary.

In a study by McQuerry, DenHartog & Barker (2016), the specific design elements in six firefighter turnout suits were studied; one control and five different ventilation designs. These five ventilation designs incorporated various ventilation features with different garment/body placements and utilized both active and passive types of ventilation. Active ventilation features require the wearer to take action to open or close the ventilation openings. Zipper openings used for ventilation are examples of active ventilation features. Passive ventilation features are features which are built into the garment; features such as grommets or an open vent are examples of passive ventilation, as they do not require any specific action from the wearer to “turn on”. All six of the turnout suits were made using the same design specifications with variations on the five ventilation designs that included: a passive open vent suit; a passive rivet vent suit; a passive moisture barrier vent suit; an active zipper vent suit; and an active vertical vent suit. The passive open ventilation suit had vents placed around the mid-torso, upper arms and mid-thigh regions. These vents placed on the turnout suit went through three layers of the protective barrier of the suit sacrificing the most thermal protection and exposing the wearer’s base layer to the outside environment. The passive rivet vented suit utilized rivets located under the arms and in the groin region to supply ventilation through the various layers of the composite. The passive moisture barrier vent was only placed in the middle layer of the composite, horizontally along the torso of the coat. The active zipper vents, like the rivet vents, were placed under the arms and in the groin region to supply ventilation when the zippers were open. The last ventilation design, the active vertical vent suit, utilized long vertical openings cut into the side seams of the coat (from the bottom of the mid-torso trim to the top of the bottom hem trim) and trousers (from the waistband to below the pant pockets) to supply the microclimate with fresh air. Tests were performed to evaluate overall heat loss including thermal and evaporative resistance. The manikin was tested with the full ensemble of the traditional United States firefighter’s turnout suit which consists of the coat, pants, helmet, hood, self-contained breathing apparatus (SCBA), gloves and boots. The coat and pants consisted of three component layers: a durable protective outer shell; a thin inner layer known as the moisture barrier which is designed to stop water and chemicals from penetrating; and the thermal layer which is directly in contact with the firefighter’s base layers (McQuerry et al., 2016).

An evaluation of the modified firefighter turnout suits was performed utilizing a sweating thermal manikin to determine the effectiveness of the ventilation designs under four different testing conditions: standing with no wind; walking with no wind; standing with wind; and walking with wind. A benefit of dressing the manikin in the full ensemble is that it enables a more accurate total heat loss (THL) measurement in a firefighter's actual working conditions. Once the THL results were calculated, it was discovered that three of the five turnout suits showed significant improvement in heat loss. Those designs which showed improvement in heat loss included: the passive open vent; active zipper vent; and active vertical vent. The passive open vent design had the highest predicted THL for all four test conditions and was most effective when using forced convection through walking with a heat loss of 175.5 W/m2 (McQuerry, 2016). The second most effective ventilation design during the walking with wind testing scenario was the active vertical vents having 143.9 W/m2. The third design that showed significant improvement was the active zipper vented design which had a predicted manikin heat loss of 131.3 W/m2. These three designs were most successful during the walking with wind test conditions and were the only three out of the five ventilation designs to have a greater manikin THL above the control garment during three out of the four testing conditions.

Ventilation Design Measurements

One way to determine the optimal ventilation design in a garment is to calculate total heat loss using the sweating thermal manikin (Wang, 2008). The sweating thermal manikin provides two distinct and important measurements: thermal insulation and evaporative resistance. Thermal insulation is defined as "the resistance to dry heat transfer by way of conduction, convection, and radiation" (ASTM, 2010b). Evaporative resistance is defined as “the resistance to evaporative heat transfer from the body to the environment” (ASTM, 2010a). It is with these measurements that THL can be calculated and evaluated (McQuerry, DenHartog, Barker & Ross, 2016).

An important consideration in the design of garments is ventilation placement, due to the differences in how areas of the body generate heat and produce sweat. In a body sweat mapping study (Smith & Havenith, 2010), areas with the highest sweat rates were identified. These included the upper, middle, and lower back regions of the torso. Supported by these results, ventilation systems in men’s business wear should be placed in these areas to be most effective. The design challenge is to maintain the traditional, professional look while still trying to achieve the main objective of keeping the body cool and comfortable.

Hybrid Variations

Sun, Au, Fan & Zheng (2015) investigated new test t-shirt designs which combined spacer and mesh structures in knit fabrics to improve thermal comfort. Spacer fabric is traditionally a three-dimensional textile that usually includes a top and bottom fabric layer and a middle connecting layer which creates loft between the two outside layers (Liu & Hu, 2011).

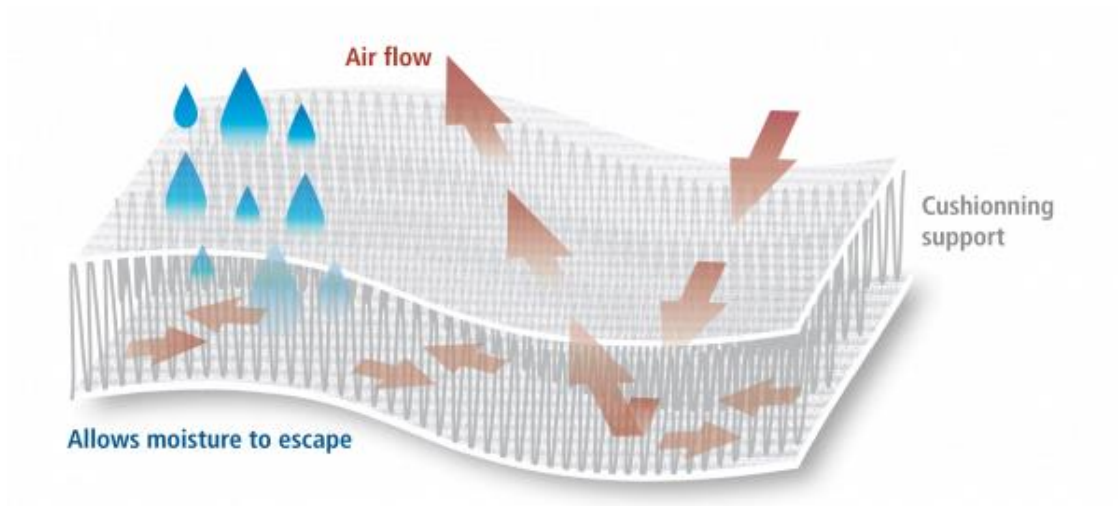


Figure 1. Breathability and Moisture Transfer of Spacer Fabric (Davimed Supplies, n.d.).

The study utilized two unique t-shirt designs which incorporated spacer fabric technology and in one instance also included a top layer of mesh. The designed t-shirts utilized these fabrics in the chest and upper back areas for increased ventilation; while the third design was a basic single jersey knit t-shirt used as a control. For all three designs, the fabrics were knitted on a circular knitting machine with polyester and nylon core-spun yarn (20% nylon / 80% polyester) (Sun et al. 2015). Using a sweating thermal manikin, the evaporative resistance (R_{et}) and thermal insulation (R_e) measurements were recorded under three different air velocities. A moisture permeability index (I_m) was also calculated in order to compare the three different designs. In addition to the trials completed on the sweating thermal manikin, wear trials were also performed, which included 30 minutes of running on a treadmill at a speed of 6.0 km/hr, followed immediately by a ten-minute rest period. Overall, the test subjects, who were wearing the new t-shirt designs while exercising, felt less wet and avoided the clingy discomfort of the fabric associated with heavy sweating. The subjects reported feeling more comfortable during the exercise and post-exercise periods. These comfort measurements were determined using a questionnaire with an assessment index (Sun et al., 2015).

In a study performed by Ho, Fan, Newton and Au (2008), ten t-shirt designs, with varying opening and mesh designs, were evaluated based on the clothing thermal insulation and moisture vapor resistance in simulated walking and standing positions. The mesh designs varied in placement on the t-shirt designs and the openings were cutout rectangular holes, stabilized with thin polyester tapes, which were attached to mitigate excessive garment distortion due to gravity and fabric draping. The results indicated that the open style and placement were better than the mesh styles in terms of releasing body heat into the environment. The t-shirt design was a standard fit, which when worn by the manikin created an air gap between the fabric layers and the body. Another important variable is the air movement which contributed to the air exchange between the microclimate around the body and the ambient microenvironment. From a design perspective, mesh ventilation panels on either side of the body were shown to be most effective for body cooling and heat and moisture transfer (Hu et al., 2008).

Morrissey and Rossi (2013) investigated the impact of fabric air permeability on the efficacy of ventilation features by measuring the changes in effective thermal insulation using three different garment ventilation features: chest zippers, back zippers and pit zippers. Testing included fabrics with high and low air permeability, under test conditions with two air flow speeds. The study utilized a thermal manikin for testing. The study concluded that the optimal type of ventilation feature with the most total heat loss (THL) was a function of ventilation feature placement with respect to the source of the air flow in terms of both air flow speed, and the direction from which the air came. Morrissey and Rossi (2013) also noted that the thermal insulation of each zone of the thermal manikin decreased when the garment was ventilated and they observed a mix of increases and decreases based on fabric permeability in addition to air flow. In high air flow, with a low permeability insulation, 67% of the thermal manikin's torso showed a decrease in thermal resistance, and the rest of the torso (33%) showed an increase in thermal resistance. With high permeability insulation and high air flow, experimental results indicated that 72% of the manikin's surface experienced a decrease in thermal resistance while only 28% of the manikin's surface experienced an increase in thermal resistance. Observations made during testing showed that in high air flow conditions, the back of the garment inflated due to the open pit zippers and chest zippers, which increased the air layers between clothing layers, in turn, increasing local pockets of thermal insulation. This observation reinforces the complexity of designing garment ventilation features and the importance of incorporating garment fit, garment openings and the target activity for which the garment is being designed.

Summary of Literature

The ventilation research and literature reviewed support the premise that clothing designed for human thermal comfort can be improved through a combination of fabric advancements, technology, and innovative ventilation design. As heat within the clothing microclimate increases; ventilation, through a variety of mechanisms, can increase air flow and sweat evaporation, thereby improving thermal comfort. This is well documented as it applies to sports apparel, outdoor clothing, and protective clothing. There is a need, however, for this same level of thermal comfort to be made available in men's business wear. Since this has not been well studied, this study will evaluate ventilation designs as applied to men's business dress shirts for increased thermal comfort. A typical men's business ensemble consists of the men's suit (jacket and pants), men’s dress shirt, and a necktie. These clothing pieces have been established as the fundamental ‘uniform’ for men’s business wear in the corporate workplace (Solnina, 2017). The men’s dress shirt is just one aspect of the suit, but men will most likely just wear the shirt and pants in the office environment, taking off their jacket as soon as they arrive and only putting it on for important meetings (Chen & Zhao, 2003).

METHODOLOGY

Through the use of mixed methods research design, applying both qualitative and quantitative methods, several ventilation designs were evaluated for study inclusion. In support of the study's purpose of improving human thermal comfort in men's business dress shirts, ventilation features and fabric technologies were incorporated for testing and evaluation.

Ventilation Design Database

A database was compiled of ventilation designs currently used in a wide variety men's and women's apparel products to determine what currently existed in the market. Based on the literature review of ventilation concepts and designs, ventilation features were evaluated and down-selected based on what could be achieved within the constraints of manufacturability and commercial viability. Down selection criteria included: uniqueness – whether this ventilation feature had already been applied to wovens and whether research already been conducted on this topic; manufacturability and commercial viability of the product; and finally, whether this ventilation feature could be incorporated into a woven men's dress shirt within the time and budget constraints of this study. Based on these criteria, several high-tech and experimental materials and fabrics were eliminated from further consideration. The laser cut hole design was selected to move forward in the research process because very little research into the application of laser cut holes in men's business clothing has been done.

Ventilation feature selection was done by the researcher and an expert evaluator based on features which could be incorporated into a woven dress shirt fabric while maintaining the fabric stability, integrity and the overall appearance of a business dress shirt which could be worn in an office environment.

Five dress shirt concept designs were then drafted using Adobe Illustrator, showing how the selected ventilation features could be incorporated into a prototype garment. Based on the research and conceptual designs, the selected ventilation feature of laser cut holes was chosen for prototype development and experimental testing.

Fabric Characteristics

Knowing from the literature review that a combination of ventilation design features and fabric technologies would be needed, existing woven and knit fabrics were selected for testing and comparison. From research into shirt designs currently on trend for a business market, a men's woven, shirting weight, button-down dress shirt was selected to be used as the control shirt for this study. This control shirt was made of 100% cotton with no unique or notable fabric treatments or technologies.

The "designed" prototype business shirt was fabricated out of Cotton Incorporated's shirting weight, TransDRY® woven fabric. The TransDRY® technology for cotton is a patented, high-performance moisture management application that allows fabrics to wick and spread perspiration to the outside of the garment where it can more easily evaporate. The TransDRY® technology begins with treated cotton yarns utilizing a special process to make them water-repellent. Blending a mix of repellent yarns with absorbent cotton yarns creates a performance cotton fabric which has a lower overall absorbent capacity allowing effective moisture management similar to a high performance synthetic fabric (TransDRY®, 2012).

The last performance shirt tested was a jersey knit men's polo shirt made by Hanesbrands, Inc. utilizing X-TEMP® fabric technology. This fabric technology was included in this study as a comparison material known for its moisture wicking ability that adapts to the wearer's body temperature. The X-TEMP® technology is a hydro-functional polymer designed to wick moisture away from the body; allowing the wearer to stay cool, dry, and comfortable. The 60% ring-spun cotton, 40% polyester blend is finished with the Hanesbrands, Inc. X-TEMP® wicking treatment which adapts to the wearer's body temperature (Hanesbrands, 2017). However, for this study the light steel color knit polo was used and its fiber content is a blend of 90% ring-spun cotton and 10% polyester. Additionally, a woven control fabric and a woven prototype fabric were needed to comply with the norm associated with men's business wear. The shirt for comparison was a jersey knit polo due to the increased trend of polos being worn in the business environment as business casual wear.

Initial Ventilation Design Testing

Evidence collected in the ventilation features database showed that the laser cut holes ventilation feature had been widely used in knit sportswear but no data was found applying this ventilation feature to a woven dress shirt. Therefore, the selected ventilation feature of laser cut holes was applied to four initial designs which exhibited four unique ventilated hole patterns (see Table 1), using Adobe Illustrator. These motifs were derived from the research done in the ventilation design database, inspired by designs already available in the marketplace. These designs were then replicated with two different hole dimensions (1/8 in. and 1/16 in.). Cotton Incorporated's woven TransDRY® fabric was selected for the prototype, therefore, the initial ventilation design testing was performed on 8 in. x 9 in. fabric samples which were cut using a Universal Laser Systems cutter (Figure 2) located in the North Carolina State University's College of Textiles.

Table 1

Ventilation Design Motifs and Patterns

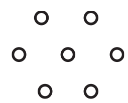
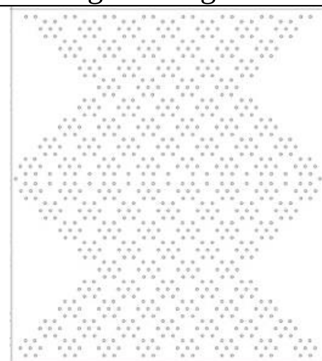
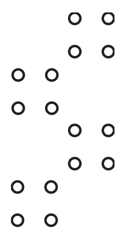
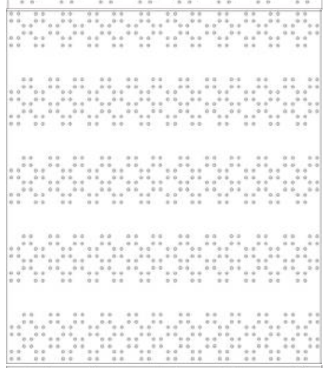
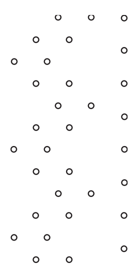
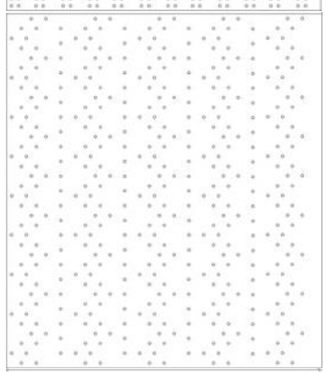
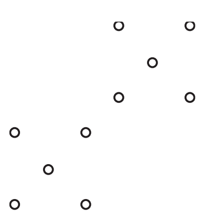
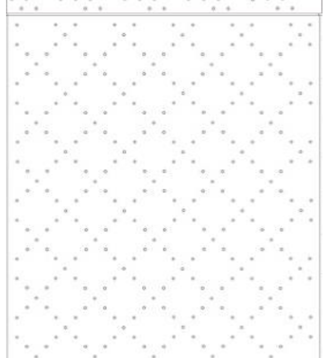
Design Number	Motif	Design Configuration
#1		
#2		
#3		
#4		

Figure 2. Universal Laser Systems, Laser Cutter.

All fabric samples, prototypes and controls were initially tested in the Physical Testing Laboratory (PTL) located in the College of Textiles at North Carolina State University. Prior to any testing or measurements, all materials (control dress shirt, knit polo, and ventilated design samples) were required to be conditioned in the laboratory environment for a minimum of 48 hours. Following the conditioning period, physical testing was performed on the various samples to gather quantitative data to determine fabric thickness and air permeability.

The ASTM D-1777-96 (2007) standard was used while recording fabric thickness sampling results. Using an AMES thickness tester, a pressure of 8.6 oz (0.6 psi) was applied to each fabric sample. Ten measurements were taken per sample in order to calculate the mean fabric thickness of each sample.

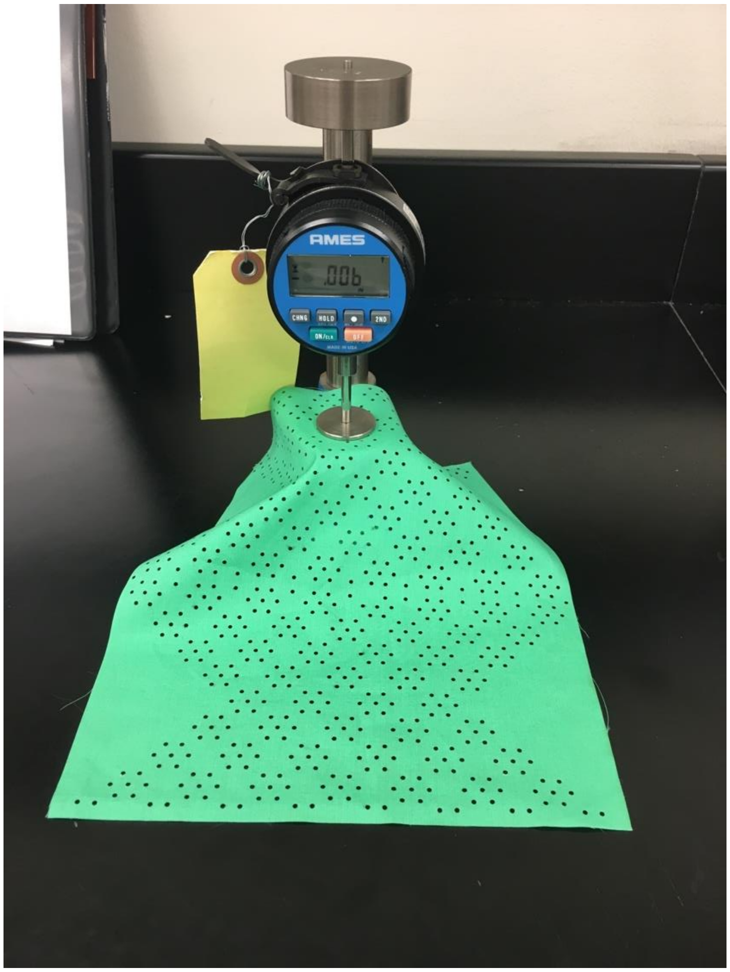


Figure 3. AMES Fabric Thickness Apparatus.

The ASTM D737-04 (2012) standard was used while measuring the air permeability through the fabric samples. Using a Frazier air permeability apparatus, the following testing procedure was followed. Initially the fabric sample was mounted over the test area and locked in place as shown in Figure 4.

Figure 4. Frazier Air Permeability Testing Apparatus.

The correct orifice size was specific to the selected or type of fabric being tested. This process was iterative in order to get the correct size. Once the correct orifice size was found for the specific fabric the machine was turned on and the rheostat was adjusted until the inclined manometer read 0.5 for equalized pressure; and the vertical manometer gage registered between 3 and 13, as shown in Figure 5.

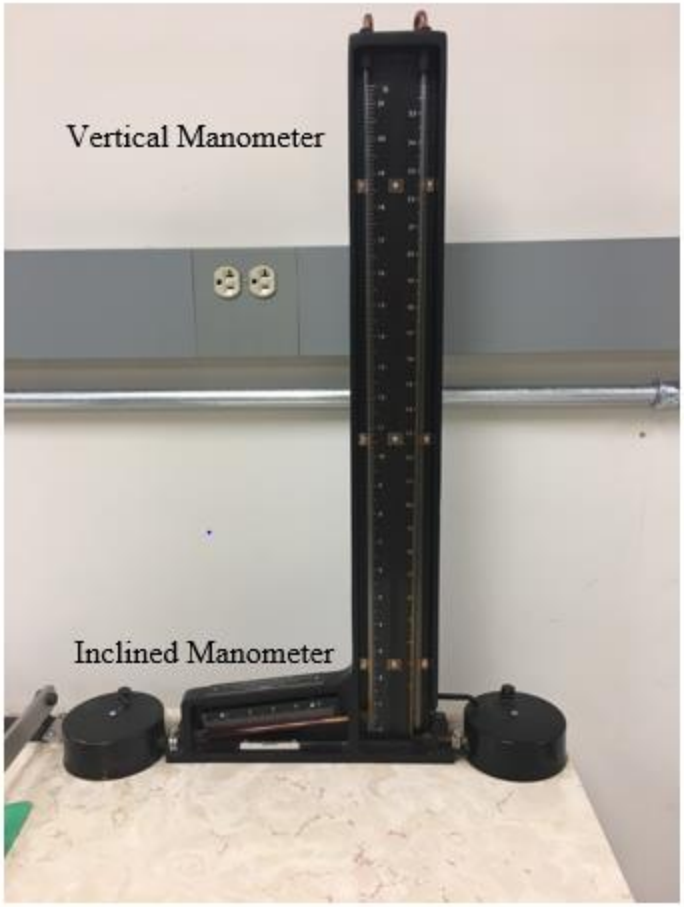


Figure 5. Pressure Gauge or Manometer.

If the reading was not within that range, then the orifice size was incorrect and had to be replaced. Testing began once the fabric was in the testing area and the rheostat was adjusted which created the differential air pressure. Once the red oil column was 0.5, then the required differential pressure had been reached and the necessary reading was noted from the right column on the vertical manometer (Figure 6). These readings were then converted into air permeability readings (CFM – cubic feet per square foot per minute) using a conversion table provided by the Physical Testing Lab. Ten tests were performed per fabric sample.

Figure 6. Pressure Gauge or Manometer Close-up.

Prototype Garment Fabrication

Since the ventilated prototype dress shirt needed to be as close in design as possible to the design of the control shirt, two control shirts were purchased from a local retailer. One dress shirt was used as the control during garment-level testing and the other dress shirt was deconstructed and used to generate pattern pieces for the ventilated prototype dress shirt. The shirt purchased for the prototype pattern was then seam ripped apart into its individual components; ironed flat; and the seam allowances were cut away. The following steps were executed to create a digital pattern file:

- Individual fabric pieces were scanned into the automated pattern digitizing system, NScan (Figure 7) by Nhega Technology (NScan, 2017)

Figure 7. NScan Scanning System.

- Pattern pieces were adjusted to remove any extraneous lines or data prior to creating a Lectra MDL file
- Using the Gerber Pattern Design software, the file was further adjusted and the seam allowances added back into the pattern pieces
- The pattern pieces were then made into a model and put into a marker using Gerber’s Easy Order software

- After the marker was made, the pattern pieces were cut out of the prototype TransDRY® fabric, using the Lectra cutter system (Figure 8).

Figure 8. Lectra Cutter System

- For the ventilated back panel of the shirt, the back panel pattern piece was exported out of the Gerber Pattern Design software and imported into Adobe Illustrator where Design 1B, Configuration A laser cut design was placed and fitted within the back panel pattern piece and saved.
- The choice of which ventilated design would be cut into the shirt back was made based on the Smith and Havenith (2010) study which outlines the sweat mapping patterns for men

- The TransDRY® fabric back panel pattern piece was taken to the laser cutter to have the Design 1B, Configuration A ventilated design, cut into it
- The prototype dress shirt was assembled in the Apparel Lab in the College of Textiles at North Carolina State University following the construction steps outlined in *Professional Sewing Techniques for Designers* (Cole and Czachor, 2014).

Upon completion of the ventilated dress shirt prototype, all three shirts: 100% woven cotton control; Hanesbrands, Inc. X-TEMP® knit polo; and the ventilated woven TransDRY® dress shirt were taken to the Textile Protection and Comfort Center (TPACC) lab for conditioning for 48 hours prior to garment-level testing. In an effort to keep the testing and results as consistent as possible, the fabrics and garments were washed to remove any chemicals or finishes from the factory prior to conditioning.

Thermal Manikin Testing

To assess the effects the ventilation design had on the garment for improved thermal comfort compared to the knitted polo and the woven control dress shirt; state of the art testing was performed in the Textile Protection and Comfort Center. Thermal comfort was primarily evaluated through thermal resistance, evaporative resistance and predicted total heat loss (THL) measured on the garment level. The following standards were followed during testing. Thermal resistance measurements were taken in accordance with ASTM F 1291 *Standard Method for Measuring the Thermal Insulation of Clothing Using a Sweating Manikin*. Evaporative resistance measurements were taken in accordance with ASTM F 2370 *Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin*. These evaporative resistance measurements were taken at 35°C which is about equivalent to the human body temperature. This temperature testing condition controlled the environmental influences so that the reported results represented the sample garments' performances.

The sweating thermal manikin system available in the TPACC lab at North Carolina State University is a "Newton" system which allows for the testing of heat and moisture management properties of clothing. The manikin has 34 individually controlled zones which simulate sweat and heat production; and each zone also has its own temperature measurement system. In addition, the sweating thermal manikin is housed in its own climate-controlled room so that thermal comfort can be simulated and studied within a given, controlled environment. See Figure 9 for a labeled diagram of the testing chamber. Additional detail is also available in Appendix D.

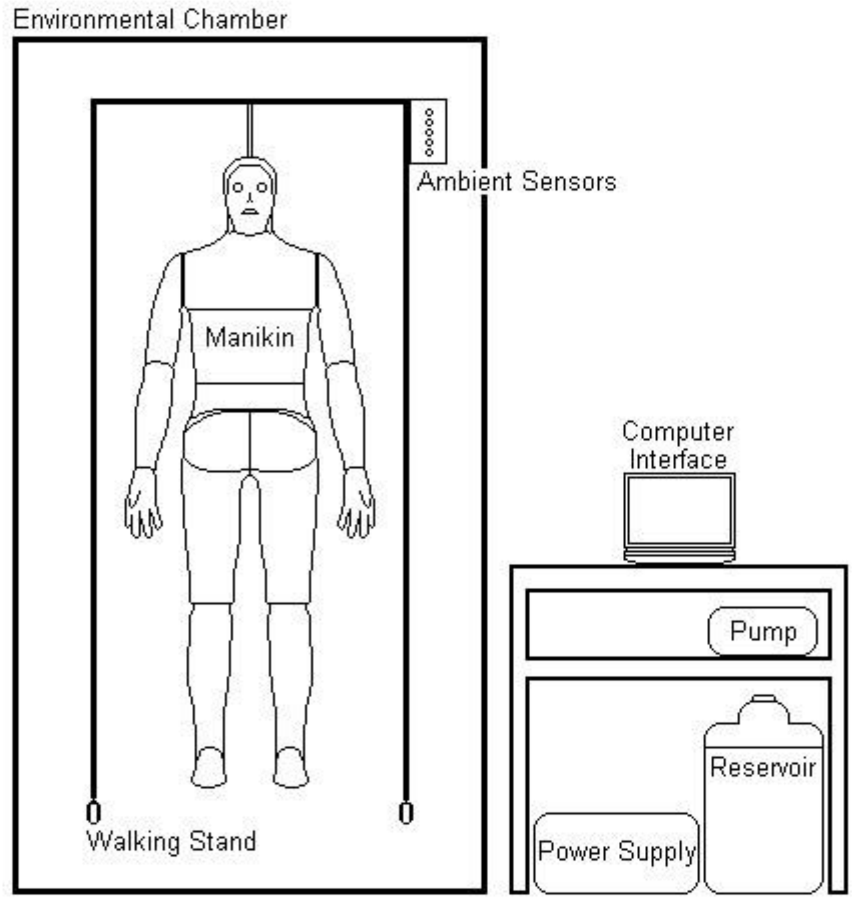


Figure 9. Testing Arrangement for the Sweating Thermal Manikin

A sweating thermal manikin was fully dressed in jeans, socks, briefs and shoes, in addition to the test shirts (control – long sleeve striped; vented – long sleeve yellow; and knit polo – short sleeve). The shirts were tucked into the jeans. Due to the fact that the knit polo was short sleeved, all testing results were limited to the ‘short sleeved’ sections of the manikin so that all comparisons between the three garments are for the same body area. On the garment level, a sweating thermal manikin was employed to discover the THL of the ventilated design, knitted polo, and plain dress shirt control garment. Testing was performed with the manikin in a standing and walking position, at a pace of 2.5 miles per hour.

Statistical Analysis

Microsoft Excel (15.32) statistical functions were used for data analysis. In order to determine the statistical significance of the measured differences in predicted total heat loss (THL) of the thermal manikin, two-sample t-tests (assuming equal variances) were completed. This allowed for the comparison of the three test garments. Additionally, a single factor, one-way ANOVA was performed for each testing condition (standing and walking) in order to identify any significant differences in THL between the woven control shirt, the woven ventilated prototype shirt and the jersey knit polo. A p-value less than or equal to 0.05 indicated a statistically significant difference in THL.

RESULTS

The tasks completed for this research study were as follows:

1. Identify ventilation designs currently implemented in a wide variety of apparel products.
2. Down-select appropriate ventilation features to incorporate into men's business wear for improved heat loss and thermal comfort.
3. Assess the selected ventilation features to determine how they affect the functionality of the garments through fabric physical testing.
4. Design and fabricate a men's dress shirt which incorporates new, original ventilation features based on ventilation research.
5. Test and compare the ventilated woven garment; with a woven control shirt; and a knitted polo currently in the market; to determine if a ventilated woven dress shirt can be a suitable alternative for increased thermal comfort in the workplace.

Assessment of Initial Ventilation Designs

In order to identify and assess the different types of ventilation designs which are currently integrated into apparel products, a thorough search of the market was performed. The various forms of ventilation designs and concepts were identified using brand websites and the literature review. After these ventilation design features were identified, the advantages and disadvantages, air flow type, and design type of each ventilation design were identified by the researcher. Air flow type was broken down into two categories: passive and active air flow. Passive air flow occurs naturally in clothing without the wearer doing anything to prompt the air flow to start; this type of air flow happens mainly at the fabric level and cannot be turned off. Active air flow occurs when the wearer performs a physical act to open up the garment for air flow like unzipping a zipper to allow air to escape. Design type was also split into two categories to determine if the ventilation was a design feature added to the garment or if the ventilation was a fabric technology integrated into the apparel at the fabric level or a combination of both. See Appendix A for the full Ventilation Design Database.

Down-Selection of Ventilation Ideas and Design of Ventilation Patterns

After the Ventilation Design Database was compiled, five ventilated shirt designs, (see Figure 10) were created using the ventilation design concepts collected from current apparel products. Design 1 incorporated laser cut holes, Design 2 had a sewn in back mesh insert with vented seams, Design 3 was a back vent with a layer of mesh underneath that ran across the should blades, Design 4 utilized SmartWeave sweat proof fabric in the back yoke of the dress shirt, Design 5 combined a vented back yoke seam with a phase change material fabric base for the entirety of the dress shirt. Based on the selection criteria outlined in the Methodology section of this paper, several high- tech options were eliminated from consideration. One of the five ventilation design ideas, Design 1 with the laser cut holes, was selected to move forward with fabric level testing, because it matched the criteria set up in the methodology. Key to the selection of laser cut holes as the ventilation feature was the fact that the application of laser cut holes in wovens and in men's business wear was unique and unexplored; and this design concept could be developed and tested within the study's time and budget constraints. See Appendix B for a detailed breakdown of each shirt and the ventilation design features used.

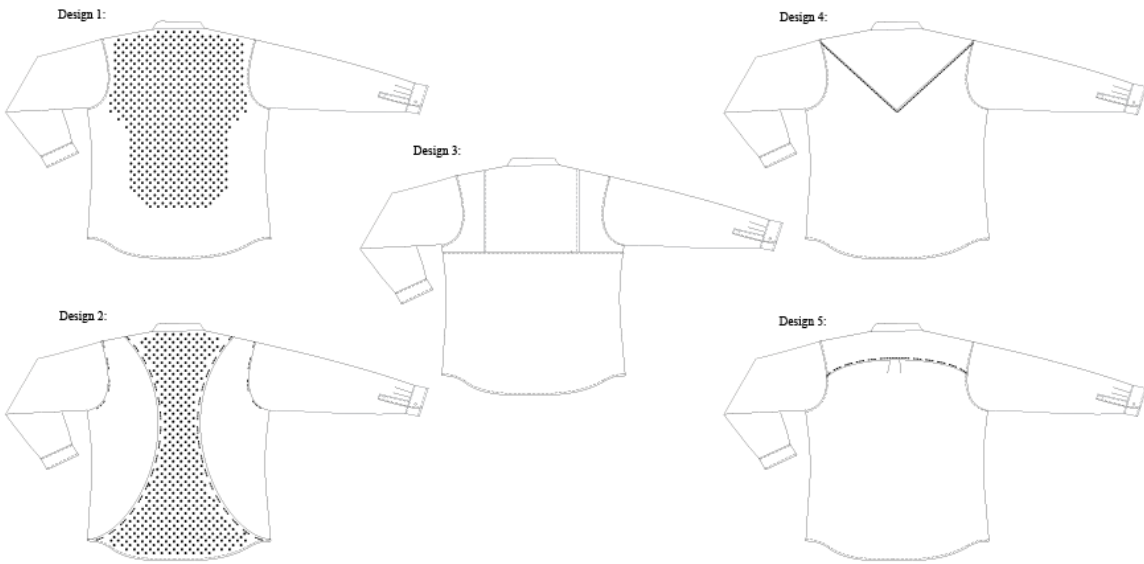


Figure 10. Ventilated Shirt Designs

In addition to the uniqueness of the use of laser cut holes in a woven dress shirt, this ventilation feature is relevant to the current market, as justified by market research done for the ventilation design database and literature review. Today, laser cut holes as a ventilation feature are widely used in the athletic / performance apparel market. This ventilation feature, has yet to be incorporated into business wear.

Using Adobe Illustrator, four motif patterns were created and each pattern was purposely placed to create unique laser cut design configurations (see Table 1). Four different laser cut hole patterns were created and each design was made at two different hole dimensions: 1/8 in. and 1/16 in. These were laser cut into 8 in. x 9 in. fabric samples of the TransDRY® fabric provided by Cotton, Incorporated.

Fabric Physical Testing Results

To determine the most effective laser cut hole design to use on the prototype garment for sweating thermal manikin testing, the various design iterations shown in Table 1 were tested at the fabric level. Three different fabrics were tested for air permeability and fabric thickness: woven 100% cotton control fabric; woven 100% cotton TransDRY® fabric (Cotton, Incorporated); and jersey knit 90% cotton/10% polyester X-TEMP® fabric (Hanesbrands, Inc.). The ventilation designs motifs were only laser cut into the TransDRY® fabric as that was the fabric chosen for the prototype ventilated garment. Eight different 8 in. x 9 in. samples were tested. See Figure 11 – Figure 14 for testing samples at both hole sizes.

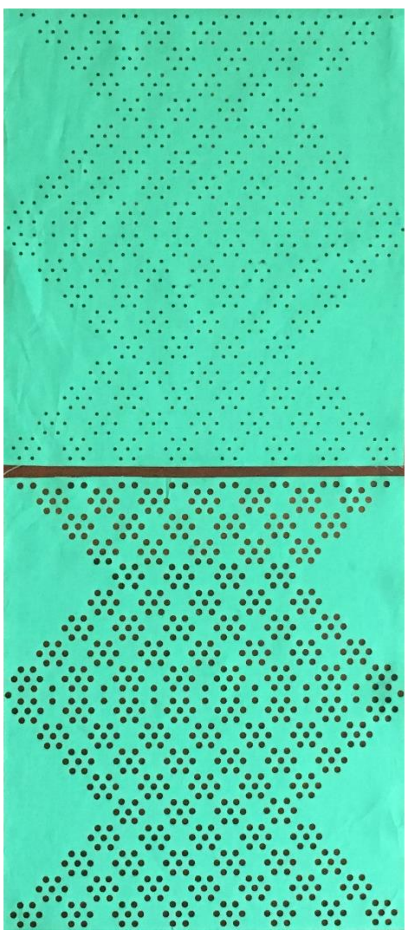


Figure 11. Design 1 Fabric Samples: 1/16 in. – Top, 1/8 in. – Bottom.

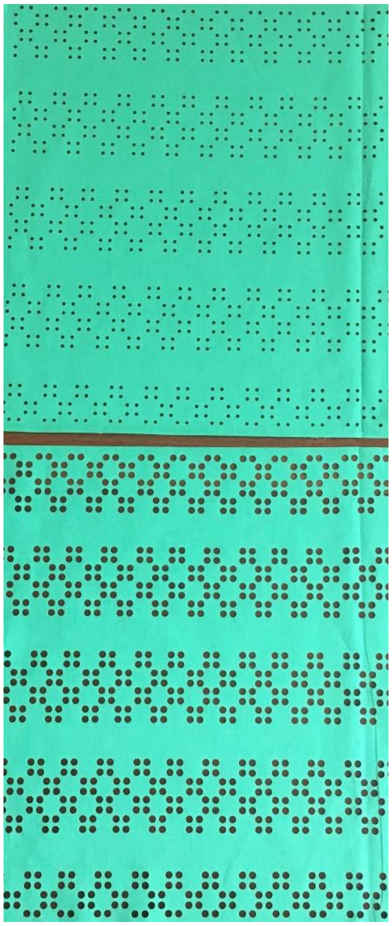


Figure 12. Design 2 Fabric Samples: 1/16 in. – Top, 1/8 in. – Bottom.

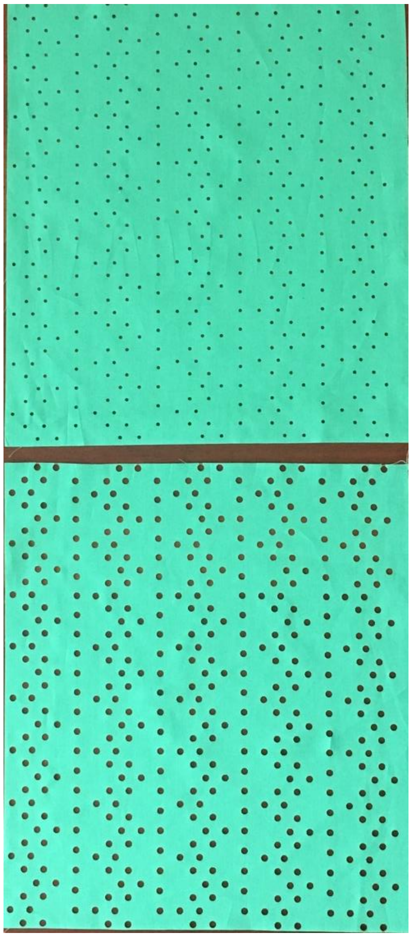


Figure 13. Design 3 Fabric Samples: 1/16 in. – Top, 1/8 in. – Bottom.

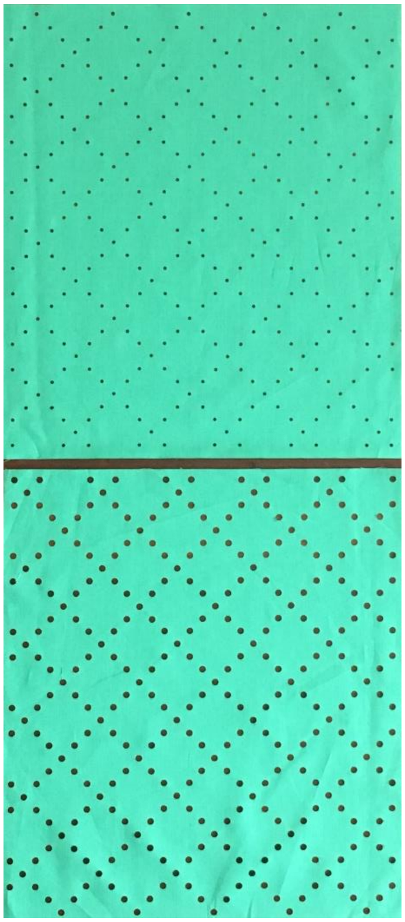


Figure 14. Design 4 Fabric Samples: 1/16 in. – Top, 1/8 in. – Bottom.

Physical testing on the various samples at the fabric level was done to determine fabric thickness, using ASTM D-1777-96 (2007), and air permeability, using ASTM D737-04 (2012). Table 2 shows the differences in fabric thickness and fiber content for the three different fabrics. It should be noted that each fabric varied in thickness and this could have had an impact on the air permeability and thermal manikin testing results.

Table 2

Physical Testing Results – Fiber Content and Fabric Thickness

Test Standard (if applicable)	Fabric 1: Control Fabric - Woven (Purchased)	Fabric 2: Hanesbrands X-TEMP® Jersey Knit Fabric (Purchased)	Fabric 3: Cotton Inc. TransDRY® Fabric Plain - Woven
Fiber Composition	100% Cotton	90% Cotton, 10% Polyester	100% Cotton
Fabric Thickness	0.010 in	0.028 in	0.006 in

Table 3 shows results from the air permeability test. The design with the greatest air permeability was the Cotton Inc. TransDRY® Fabric 3, Design 1, with a 1/8 in. hole diameter and an average air permeability reading of 492.8 CFM. The least air permeable was Fabric 1 – control fabric, woven, 100% cotton with no ventilation features and an average air permeability reading of 83.05 CFM. The testing conditions and orifice size was variable due to the range allowed within the specifications of the standard.

Table 3

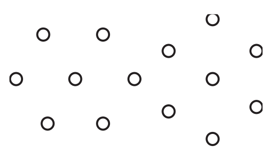
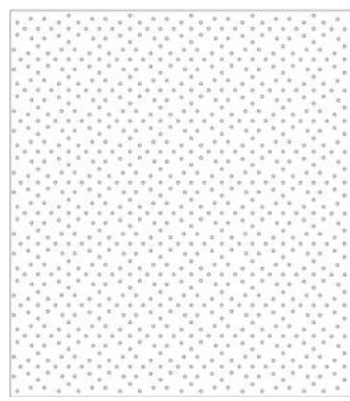
Physical Testing Results - Air Permeability

	Hole Size	Date Tested	Testing Conditions (^oF / %RH)	Orifice Size	Air Permeability (CFM) ASTM D737 - 04 (2012)
Fabric 1: Control Fabric (Purchased)	N/A	10/11/17	69 ^oF / 66%RH	8mm	83.05
Fabric 2: Hanesbrands X-TEMP® Jersey Knit Fabric (Purchased)	N/A	8/18/17	69 ^oF / 65%RH	8mm	129
Fabric 3: Cotton Inc. TransDRY® Fabric Plain	N/A	8/4/17	69 ^oF / 64%RH	8mm	108.38
Fabric 4/5: Cotton Inc. TransDRY® Fabric Design 1	$1/8^{th}$ inch	8/4/17	69 ^oF / 64%RH	16mm	492.8
	$1/16^{th}$ inch	8/4/17	69 ^oF / 64%RH	11mm	213.6
Fabric 6/7: Cotton Inc. TransDRY® Fabric Design 2	$1/8^{th}$ inch	8/4/17	69 ^oF / 64%RH	16mm	426.5
	$1/16^{th}$ inch	8/4/17	69 ^oF / 64%RH	11mm	195.5
Fabric 8/9: Cotton Inc. TransDRY® Fabric Design 3	$1/8^{th}$ inch	8/4/17	69 ^oF / 64%RH	11mm	253.6
	$1/16^{th}$ inch	8/4/17	69 ^oF / 64%RH	8mm	126.9
Fabric 10/11: Cotton Inc. TransDRY® Fabric Design 4	$1/8^{th}$ inch	8/4/17	69 ^oF / 64%RH	11mm	215.2
	$1/16^{th}$ inch	8/4/17	69 ^oF / 64%RH	8mm	131.7

While performing the preliminary testing, the researcher found that while the 1/8 in. design samples were the most air permeable, they were found to be too open and lacking in structural integrity of the fabric. This was determined based on the amount of exposed skin that from a design point seemed inappropriate for the work environment from a subjective standpoint. A balance between air permeability and meeting ‘business appropriate’ standards was critical in creating a successful design for this research. Due to these shortcomings, all 1/8 in. designs were eliminated from further consideration. A new laser cut hole design was developed which was a variation of one of the original designs with a modified motif, rotated 90^{o} with 1/16 in. hole diameter. This design was added to provide an additional ventilation design for consideration and testing. This new design then followed the previously outlined methodology for sample cutting, conditioning, and fabric level testing (see Table 4, Design 1B).

Table 4

Additional Ventilation Design Motif and Pattern

Design Number	Motif	Design Iterations
#1B		

With this new design, additional physical testing had to be performed as depicted in Table 5. See Figure 15 for Design 1B testing sample.

Figure 15. Design 1B Fabric Sample.

Table 5

Physical Testing Results - Air Permeability

Fabric 12: Cotton Inc. TransDRY® Fabric Design 1B	1/16th inch	8/31/17	70 °F / 65%RH	11mm	214.4

With an average air permeability reading of 214.4 W/m^2, this new design became the most air permeable of the 1/16 in. hole diameter designs as seen in the graph in Figure 16. It became the highest performing ventilation design which still met modesty standards needed for a workplace environment.

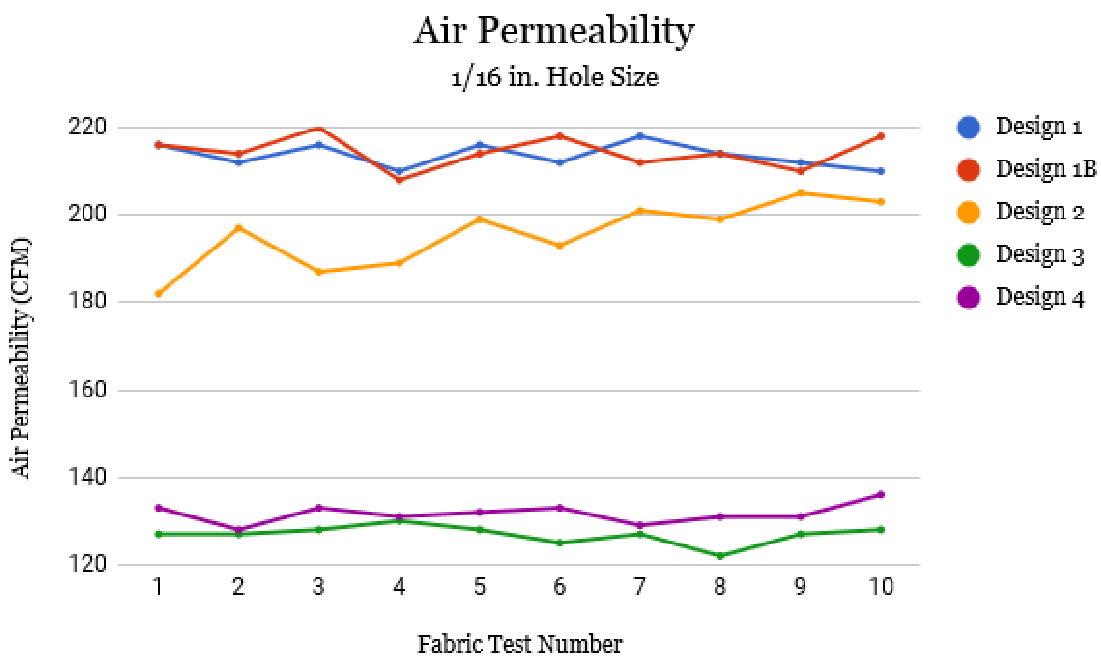


Figure 16. Graph Comparing 1/16 in. hole Designs - Air Permeability Results

Design and Fabrication of Men's Dress shirt

Having selected the prototype ventilation design, three dress shirt sketches were created to showcase various ways laser cut hole designs could be placed on the back panel of the garment. These design shirt samples were then reviewed by the researcher and an expert evaluator to determine the shirt design to move forward with to the prototype fabrication phase of development (see Figure 18). This choice was made based on the Smith and Havenith (2010) study which outlines the sweat mapping patterns for men. Figure 17 shows the areas of highest sweat rates are the upper, middle and lower back areas. The top laser cut hole design in Figure 18, Design A outlined in green, was chosen to move forward as it covered the areas of back with the highest sweat production and was the most aesthetically pleasing to the researcher and the expert evaluator. The garment fabrication phase was performed at the North Carolina State University's Apparel Lab in the College of Textiles.

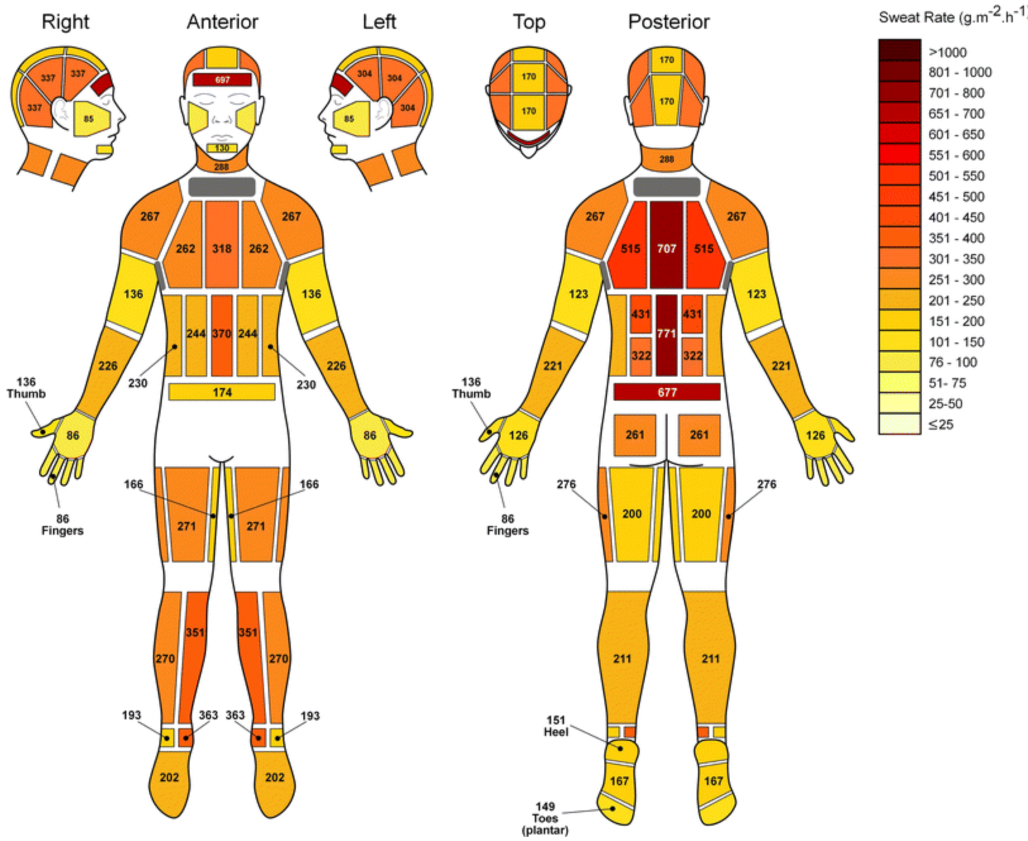


Figure 17. Absolute regional median sweat rates of male athletes at 55% VO2max exercise intensity (Smith & Havenith, 2010).

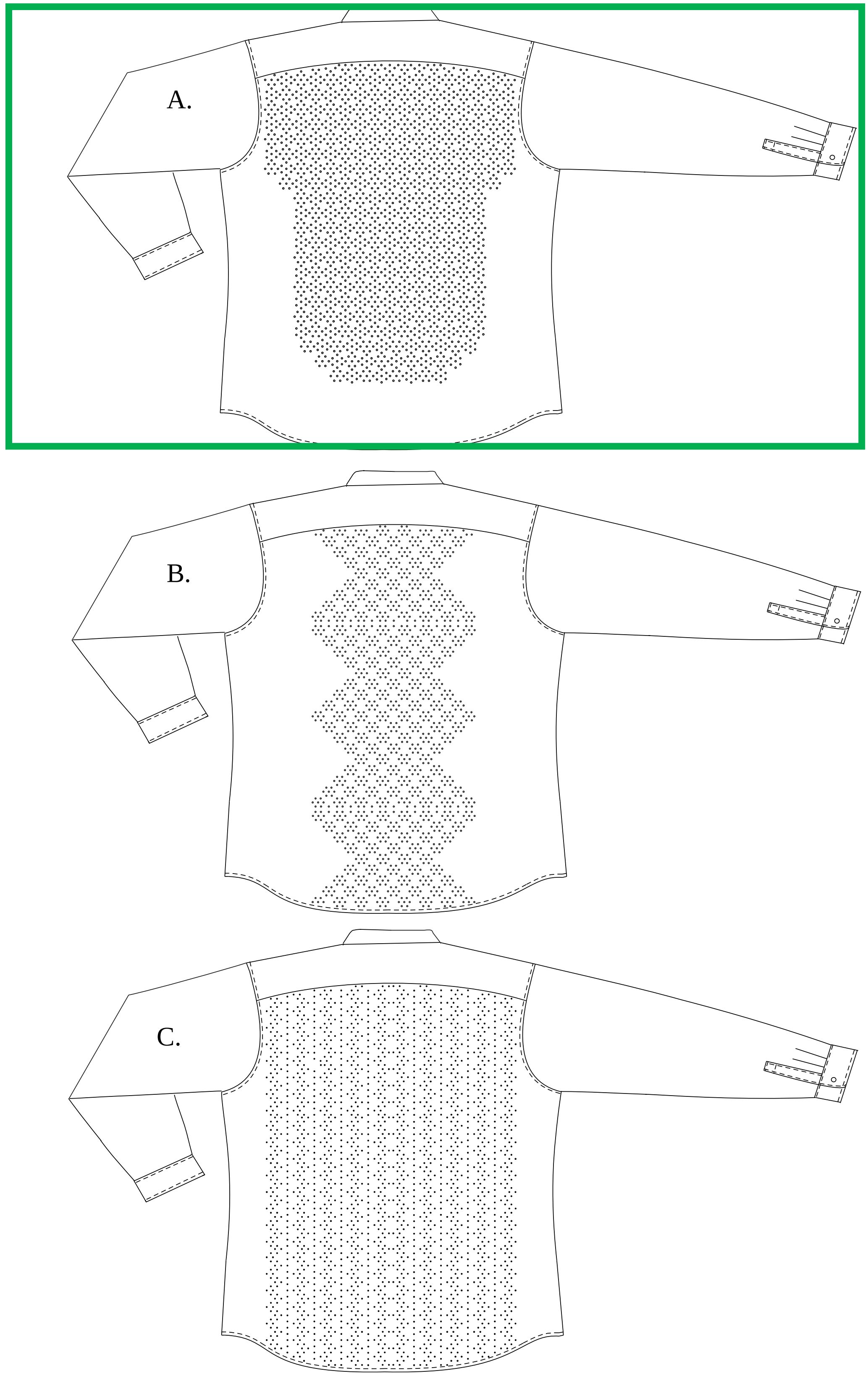


Figure 18. Laser Cut Hole Ventilated Shirt Designs.

Thermal Manikin Testing Results

The garment level testing was performed in the TPACC lab in the College of Textiles at North Carolina State University. Three garments of the three different fabrics selected for evaluation were provided for testing using the sweating thermal manikin in order to determine the evaporative and thermal resistance for each design as well as the calculated predicted total heat loss ($Q_{predicted}$ or Q value). The testing was performed over a two-week period and consisted of three repetitions of each testing protocol (standing and walking). The testing conditions used are outlined in Tables 6 and 7.

Table 6

Testing Conditions – Thermal Resistance

	Standing	Walking
Air Temperature (^oC)	20	20
RH (%)	50	50
Air Speed (m/s)	0.4	0.7
Walking Speed (mph)	0	2.5
Skin Temperature (^oC)	35	35

Table 7

Testing Conditions – Evaporative Resistance

	Standing	Walking
Air Temperature (^oC)	35	35
RH (%)	40	40
Air Speed (m/s)	0.4	0.7
Walking Speed (mph)	0	2.5
Skin Temperature (^oC)	35	35

For the standing tests, the air speed was 0.4 meters/second (m/s) which is representative of ‘still’ air, to keep the testing conditions consistent and controlled. There is no such thing as zero wind, as air is always moving. For the walking conditions, the manikin walked at 2.5 miles/hour or 55 double steps per minute with an air speed of 0.7 m/s. This was designed to replicate the speed of moving around an office environment, going to lunch, and commuting.

Due to the fact that one of the garments was a short sleeve polo, the body sections of the manikin that were evaluated for the purposes of this study were limited to only the short sleeve shirt zones and corresponding data for direct comparison between the test garments. Figure 19 shows the body zones evaluated of the sweating thermal manikin.

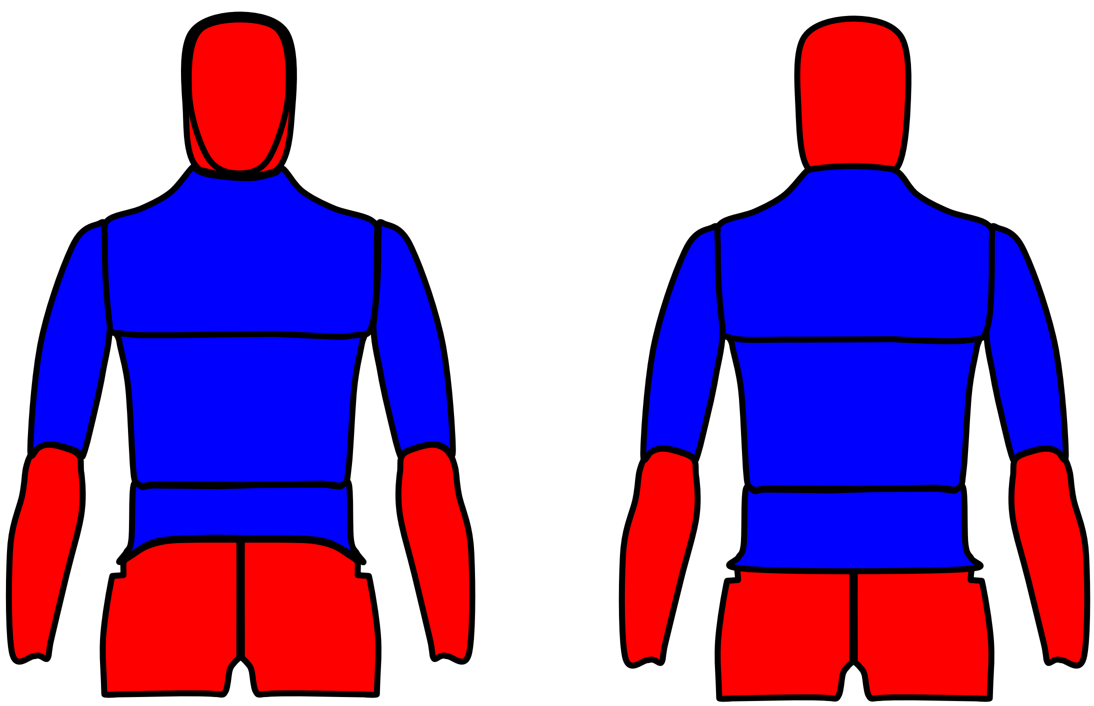


Figure 19. Body Sections Evaluated for Short Sleeve Shirt Zones (Blue Sections).

Three shirts were provided for testing and were labeled A, B, C. These letters correspond to: A – control – 100% woven cotton, woven – long sleeve striped shirt; B – selected design ventilated prototype – TransDRY®, woven – long sleeve yellow shirt; and C – knit polo – X-TEMP® - short sleeve grey. The complete test report which contains a summary and detailed testing data is provided in Appendix D.

The summarized testing results for the standing and walking conditions for the short sleeve shirt zone tests are listed in Tables 8 and 9.

Table 8

Average R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted,\ 25C,\ 65RH}$ for Short Sleeve Shirt Zones - Standing

Ensemble	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted,\ 25C,\ 65RH*}$ (W/m^2)
A	**0.1827**	**0.02483**	**0.1195**	**0.01401**	**1.18**	**0.45**	**198.5**
B	**0.1709**	**0.02231**	**0.1076**	**0.01154**	**1.10**	**0.47**	**218.6**
C	**0.1690**	**0.02288**	**0.1058**	**0.01222**	**1.09**	**0.45**	**215.1**

Table 9

Average R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted,\ 25C,\ 65RH}$ for Short Sleeve Shirt Zones - Walking

Ensemble	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted,\ 25C,\ 65RH*}$ (W/m^2)
A	**0.1190**	**0.01357**	**0.0661**	**0.00494**	**0.77**	**0.54**	**346.8**
B	**0.1130**	**0.01202**	**0.0601**	**0.00349**	**0.73**	**0.57**	**385.2**
C	**0.1146**	**0.01396**	**0.0620**	**0.00545**	**0.74**	**0.50**	**342.7**

As indicated in the results in Table 8, the ventilated prototype (Shirt B – 218.6 W/m^2) demonstrated a slightly higher Q value than either the control (Shirt A – 198.5 W/m^2) or the knit polo (Shirt C – 215.1 W/m^2) for the standing test scenarios. This indicated that the ventilated design helped dissipate the heat and performed on par with the Hanesbrands, Inc. X-TEMP® knit polo.

For the walking test scenarios, as outlined in Table 9, the ventilated prototype (Shirt B) had a greater Q value (385.2 W/m^2) than both the control (Shirt A- 346.8 W/m^2) and the knit polo (Shirt C – 342.7 W/m^2). This indicates that the predicted total heat loss of the ventilated design was potentially greater that the other shirts being tested. This could mean that the wearer of the ventilated dress shirt could feel more comfortable in a business environment while in motion. For this set of results, the Q values were more disparate, with a 42.5 W/m^2 difference between Shirt B and Shirt C.

Statistical Analysis Results

The testing performed per the ASTM standards was done for three test cycles therefore, the calculations were performed using this small sample size. See Appendix F for full statistical data used for analysis and Table 10 and Table 11for the summarized results.

Standing – Static Test Condition

For the standing with still air test condition, the p-value less than 0.05 (0.01) indicates the vented prototype dress shirt had a significantly greater THL than the control dress shirt. The 20 W/m2 improvement was statistically significant. The knit polo also had a significantly higher THL compared to the control dress shirt in the static test condition. No significant difference was found between vented prototype and knit polo as the p-value was greater than 0.05 (0.54).

Walking with wind – Active Test Condition

In the walking with wind test condition, the p-value much less than 0.05 (5.5611E-06) indicated in the one-way ANOVA, shows significant differences in THL between the shirts. When comparing the Q values between the ventilated prototype (385.2 W/m^2) and the comparison knit polo (342.7 W/m^2) the difference of 42.5 W/m^2 is significantly different and could be considered a meaningful difference and suggests that the wearer may be able to detect a tactile and sensory difference in thermal comfort between the two shirts. This hypothesis would need to be validated through future wear trial testing.

Table 10

t-Test: Two-Sample Assuming Equal Variances Results Overview

P(T<=T) two-tail

	Predicted Heat Loss Potential (Q value) - Standing with still air	*Predicted Heat Loss Potential (Q value) - Walking with wind*	*Total Thermal Resistance (R_t) - Standing with still air*	*Total Thermal Resistance (R_t) - Walking with wind*	*Total Evaporative Resistance (R_{et}) - Standing with still air*	*Total Evaporative Resistance (R_{et}) - Walking with wind*
Control Shirt / Ventilated Design Shirt	0.016980491	8.02401E-05	0.002256018	0.007026441	0.02948168	0.000105597
Ventilated Design Shirt / Comparison Knit Polo Shirt	0.538401664	0.000138646	0.319290855	0.527642166	0.486956186	0.000172095
Control Shirt / Comparison Knit Polo Shirt	0.007143728	0.154140062	0.001643413	0.161622905	0.020233799	0.037279256

Table 11

ANOVA: Single Factor

	Predicted Heat Loss Potential (Q value) - Standing with still air	*Predicted Heat Loss Potential (Q value) - Walking with wind*	*Total Thermal Resistance (R_t) - Standing with still air*	*Total Thermal Resistance (R_t) - Walking with wind*	*Total Evaporative Resistance (R_{et}) - Standing with still air*	*Total Evaporative Resistance (R_{et}) - Walking with wind*
P-value: ANOVA Between Groups	0.010143564	5.5611E-06	0.000449771	0.067826134	0.023738654	1.0512E-05

CONCLUSIONS AND DISCUSSION

Test results from the sweating thermal manikin show that in a standing position with still air, shirt B (ventilated prototype) had a slightly greater potential for increased ventilation and heat loss than the control (woven) or the Hanesbrands X-TEMP ® knit polo. This difference was determined to be statistically significant. Under walking conditions, the difference between the ventilated prototype and the comparison knit polo was determined to be a statistically significant difference. This difference may mean the bellows effect achieved through motion increased the effectiveness of the ventilation design and, therefore, the thermal comfort of the wearer, however, further testing would need to be performed to prove this.

The following conclusions from this study address the original research objectives. The ventilated business dress shirt performed equal to or better than knit polo shirt and the woven control shirt in predicted total heat loss and these differences were found to be statistically significant. The design challenge to maintain the traditional, professional look of a classic men's dress shirt while still trying to achieve the main objective of keeping the body cool and comfortable was achieved through the strategic placement of the laser cut holes ventilation feature on the shirt back. It is through the combination of design and technology that optimal thermal comfort can be achieved. Both fabric technology advances (TransDRY® and X-TEMP®) and ventilation features were needed to provide the heat loss and associated thermal comfort performance, making this project a hybrid ventilation design. Ventilation features and fabric technical advances may be a more efficient way to regulate the personal microclimate than to regulate an entire building's environment to achieve that same comfort result.

This research represents an initial exploration of a conceptual ventilated woven shirt design that incorporates laser cut holes as a means of increased ventilation. This project was performed as a proof-of-concept applied to men's business wear category. The potential applicability of the research to increase the thermal comfort of the worker exists in business environments and non-climate controlled environments. Researchers with interests in the area of ventilation and thermal comfort and shirting companies looking for an untapped area to explore could find this research useful.

The findings and conclusions made from this study help illuminate another application for ventilation in the form of laser cut holes. The conclusions generated from this study represent preliminary data on the effectiveness of clothing ventilation designs in men's business wear for improved comfort performance and provides useful knowledge to the textiles and apparel industry on an area that has yet to be explored to its full potential.

STUDY LIMITATION

This study has the following limitations:

Design ventilation features were limited in order to maintain the 'business appropriateness' of a dress shirt as defined in the literature review.

Two shirt styles were utilized (knit polo and woven dress shirt) instead of a full business suit. Therefore, the study results are limited to ventilation of the upper half of the body with these specific garments.

Testing was performed on a sweating thermal manikin in a controlled laboratory environment where temperature, humidity and wind speeds were regulated. This limited the results to pure data readouts rather than human experimental feedback, usually provided in wear trials.

The manikin had limited mobility due to the rigid nature of its construction; and the testing performed included standing measurements and a walking simulation with arm movement at a controlled speed.

The specific fabrics utilized were limited to existing textile technology in commercially available fabrics.

FUTURE WORK

Considering this research project was originally designed as a proof of concept project and was the first project on ventilation to venture into the business wear category, there are several suggestions for future research and future applications that need to be further explored.

Incorporation of additional fabric level testing and measurements are needed to isolate and quantify meaningful differences in design heat loss. An example of this would be to measure the open area (the number of ventilation holes per square in) and calculate how this might affect the overall air permeability data. Adding additional fabric level testing will help to better determine the true predicted THL associated with the ventilation design feature.

Include and evaluate additional high-tech materials and fabrics such as nanoPE in order to investigate potential benefits from fabric and material advancements for enhanced thermal comfort (Hsu et al., 2016).

For full garment testing, an exploration into how the dress shirt feels on the body should be investigated. This project used a sweating thermal manikin that gave numerical data read outs rather than opinions and sensory data. With that in mind, a series of wear trials with human participants would be a logical next step. An advantage of a human wear trial is the feedback that could be gained on whether or not they can discern a sensory difference between the TransDRY® ventilated dress shirt, and the Hanesbrands X-TEMP® knit polo.

In addition to human wear trials, creating a second prototype garment could be another potential avenue for growth of this project. The second dress shirt could use a different laser cut hole design or a different design configuration as a comparison example and to see if a variation in design could play a role on evaporative resistance, thermal resistance and the THL results.

This project focused on incorporating ventilation design ideas into a men's dress shirt for improved comfort performance. Starting with the dress shirt gave focus to the project that allowed the researcher to solidify the order of operations and the framework for this type of study. Now that the foundation has been established, future areas of study should include an assessment of different ventilation ideas in men's dress pants and suit jackets.

Finally, a study focused on women's business wear should be investigated. Women face the same struggles with office attire and comfort as men, therefore, a research study focused on womenswear to improve comfort performance would be another potential research opportunity. With climate temperatures on the rise, incorporating ventilation in multiple consumer apparel markets is needed now more than ever. Engineering models and simulations could help predict how much higher temperatures and still maintain the wearer's thermal comfort. In addition, commuter options are changing according to the type of geographic location within which office workers function – in many areas walking and biking to work are increasing in popularity and necessitate some concessions in wardrobe to achieve maximum comfort.

REFERENCES

ASTM. (2010a). Standard test method for measuring the evaporative resistance of clothing using a sweating manikin. West Conshohocken, PA: *American Society of Testing and Materials*. doi:10.1520/F2370-10.Copyright

ASTM. (2010b). Standard test method for measuring the thermal insulation of clothing under a heated manikin. West Conshohocken, PA: *American Society of Testing and Materials*. doi:10.1520/F1291-10.responsibility

Bouskill, L., Havenith, G., Kuklane, K., Parsons, K., & Withey, W. (2002). Relationship between clothing ventilation and thermal insulation. *AIHA Journal*, *63*(3), 262–8. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12173174

Chen D., & Zhao, Q. (2003). A study on clothing pressure for men's suit comfort evaluation. *International Journal of Clothing Science and Technology*, *15* (5), 320-334. Retrieved from https://doi-org.prox.lib.ncsu.edu/10.1108/09556220310492598

Centeno, A., (2014). The appropriate men's attire for every occasion. *Real Men Real Style*. Retrieved from http://www.businessinsider.com/the-appropriate-mens-attire-for-every-occasion-2014-9

Cole, J., & Czachor, S. (2014). *Professional Sewing Techniques for Designers*. New York: Bloomsbury

Creswell, J, Plano Clark, V., Gutmann, M. & Hanson, W. (2003). Advanced mixed methods research designs. In A. Tashakkori and C. Teddlie (Eds), *Handbook on Mixed Methods in the Behavioral and Social Sciences*. Thousand Oaks, CA: Sage Publications.

Dai, W. & Havenith, G. (2015). Effect of clothing ventilation on thermal insulation and vapor resistance. Retrieved from https://www.researchgate.net/publication/268354227_Effect_of_clothing_ventilation_on_thermal_insulation_and_vapor_resistance

Davimed Supplies. (n.d.). *Laboratory test*. Retrieved from https://davimed-supplies.com/Laboratory-Test

Dukes-Dobos, F., Reischl, U., Buller, K., Thomas, N., & Bernard, T. (1992). Assessment of ventilation of firefighter protective clothing. *ASTM Performance of Protective Clothing*, *4*, 629–633. Retrieved from http://209.195.157.104/DOWNLOAD/STP19192S.389810-1.pdf

Eckman, M., & Wagner, J. (1995). Aesthetic aspects of the consumption of fashion design: the conceptual and empirical challenge. *Advances in Consumer Research*, 22, 646-649.

Erwin, M., & Kinchen, L. (1974). *Clothing for moderns*. New York: Macmillan

Gao, C., Kuklane, K., Wang, F., & Holmer, I. (2012). Personal cooling with phase change materials to improve thermal comfort from a heat wave perspective. *Indoor Air*, *22*, 523-530. doi: 10.1111/j.1600-0668.2012.00778.x

Ho, C., Fan, J., Newton, E., & Au, R. (2008). Effects of athletic t-shirt designs on thermal comfort. *Fibers and Polymers, 9*(4), 503-508.

Hsu, P., Song, A., Catrysse, P., Liu, C., Peng, Y., Xie, J…. & Cui, Y. (2016). Radiative human body cooking by nanoporous polyethylene textile. *Science, 353*(6303), 1019-1023.

Liu, Y., & Hu, H. (2011). Compression property and air permeability of weft-knitted spacer fabrics. *The Journal of the Textile Institute*, *102*(4), 366-372.

McQuerry, M. (2016). Clothing modifications for heat strain reduction in structural firefighter protective clothing systems.

McQuerry, M., DenHartog, E., Barker, R., & Ross, K. (2016). A review of garment ventilation strategies for structural firefighter protective clothing. *Textile Research Journal, 86*(7), 727–742. doi: 10.1177/0040517515595029

McQuerry, M., DenHartog, E., & Barker, R. (2016). Garment ventilation strategies for improving heat loss in structural firefighter clothing ensembles. *AATCC Journal of Research, 3*(3), 9–14. doi: 10.14505/ajr.3.3.2

Mendell, M., & Mirer, A. (2009). Indoor thermal factors and symptoms in office workers: findings from the US EPA BASE study. *Indoor Air, 19*(4), 291-302.

Morrissey, M. & Rossi, R. (2013). The influence of fabric air permeability on the efficacy of ventilation features. *International Journal of Clothing Science and Technology, 25*(6), 440-450.

NASA. (2009). Phase change fabrics control temperature. *Spinoff 2009*, 84-85. Retrieved from https://www.nasa.gov/pdf/413410main_PhaseChange.pdf

Parkova, I., & Vilumsone, A. (2011). Microclimate of smart garment. *Scientific Journal of Riga Technical University 6*, 99-103.

Phase change materials. (2004). *Textile World*. Retrieved from http://www.textileworld.com/textile-world/features/2004/03/phase-change-materials/

Ruckman, J., Murray, R., & Choi, H. (1999). Engineering of clothing systems for improved thermos-physiological comfort: The effect of openings. *International Journal of Clothing Science and Technology, 11*(1), 37–52.

Smith, C., & Havenith, G. (2010). Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia. *European Journal of Applied Physiology*, 1–14. doi:10.1007/s00421-010-1744-8

Smith, C., & Havenith, G. (2010). Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia. *European Journal of Applied Physiology*, 1–14. doi:10.1007/s00421-010-1744-8

Solnina, J. (2017). How to master business attire for men. *The Idle Man*. Retrieved from https://theidleman.com/manual/advice/business-attire-for-men/

Sun, C., Au, J., Fan, J., & Zheng, R. (2015). Novel ventilation design of combining spacer and mesh structure in sports t-shirt significantly improves thermal comfort. *Applied Ergonomics 48*, 138-147.

Ueda, H., Inoue, Y., Matsudaira, M., Araki, T., & Havenith, G. (2006). Regional microclimate humidity of clothing during light work as a result of the interaction between local sweat production and ventilation. *International Journal of Clothing Science and Technology, 18*(4), 225-234. doi 10.1108/09556220610668473

Vokac, Z., Kopke, V., & Keul, P. (1973). Assessment and analysis of the bellows ventilation of clothing. *Textile Research Journal, 43*(8), 474–482. doi: 10.1177/004051757304300806

Wang, F. (2008). A comparative introduction on sweating thermal manikin “Newton” and “Walter”. 1-7. Paper presented at 7th International Thermal Manikin and Modelling Meeting, University of Coimbra, Portugal.

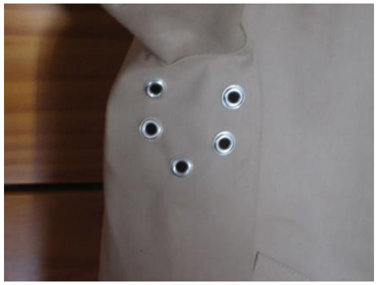
Ward, A. (2008). How does self-image impact employee performance. Retrieved from https://www.ncu.edu/blog/how-does-self-image-impact-employee-performance

Watkins, S. (1984). *Clothing the Portable Environment* (First.). Des Moines, Iowa: The Iowa State University Press.

Weldon, K. (2000). The men's business suit: Extinct, or just evolving? *Apparel Industry Magazine*, *61*(10), 14. Retrieved from http://proxying.lib.ncsu.edu/index.php?url=http://search.proquest.com.prox.lib.ncsu.edu/docview/215435753?accountid=12725

APPENDICES

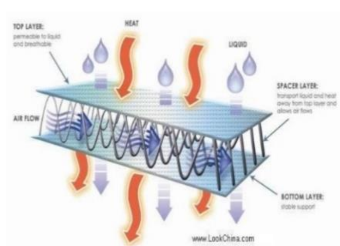
Appendix A: Ventilation Design Database

Type of Ventilation	Company Example	Picture Example	Air Flow Type	Advantages/ Disadvantages	Placement Orientation	Design Type
Armpit Zippers	The North Face		Active	Advantages: Zippers can be opened and closed based on wearer ventilation preferences. Disadvantages: Zippers are usually only placed on an external layer that can be removed; not placed on a base layer that has exposure to skin.	Vertically placed along the underarm seam Length is variable, type (visible/exposed, etc.) is variable	Design Feature
Rivets	J. Crew		Passive	Advantages: Rivets provide some ventilation to the region in which they are applied; usually found in raincoats Disadvantages: Rivets provide very localized ventilation (McQuerry, 2016)	Holes are added usually under the arms and are finished using grommets	Design Feature

Type of Ventilation	Company Example	Picture Example	Air Flow Type	Advantages/ Disadvantages	Placement Orientation	Design Type
Laser Cut or Punched Holes (Not Mesh)	Under Armour		Passive	Advantages: Laser cut holes give the garment ample ventilation; can vary in size. Disadvantages: May cause some translucent areas and can affect structural stability; size /placement dependent	Can be placed anywhere on a garment usually found on the back and side regions of a garment	Design Feature
Sewn in Mesh	Nike, Café du Cycliste	 	Passive	Advantages: Using a breathable, sewn in mesh, air is constantly ventilated during motion and at rest, allowing the body to cool Disadvantages: Adds unnecessary seams which can create bulk; mesh applications are typically in athletic wear.	Sewn in panels of breathable mesh can be placed along style lines and around areas that produce sweat	Design Feature and Fabric Technology

Type of Ventilation	Company Example	Picture Example	Air Flow Type	Advantages/ Disadvantages	Placement Orientation	Design Type
Mesh Integrated into the Knit	lululemon		Passive	Advantages: Seamless design provides the garment with more durability Disadvantage: Once the fabric/ garment is produced the placement of the ventilation is fixed, this can cause issues with sizing and grading	This type of ventilation is incorporated into the design at the knitting phase.	Fabric Technology
Back Vent with Mesh	Columbia PFG		Passive	Advantages: Can be work in a variety of setting due to the mesh ventilation being covered by a back vent panel Disadvantages: The back vent panel that covers the mesh may prohibit the amount of ventilation that an uncovered mesh panel could provide	large mesh panel covering the back; area that produces the most sweat and heat; that is then covered by a back vent to allow air flow but preserve modesty	Design Feature and Fabric Technology

Type of Ventilation	Company Example	Picture Example	Air Flow Type	Advantages/ Disadvantages	Placement Orientation	Design Type
Phase Change Material	Ministry of Supply		Passive	Advantages: the Future Forward dress shirt is the first dress shirt to use NASA-engineered Phase Change Materials for temperature regulation. Phase-Change Materials act like a battery for body heat. They absorb excess heat when you’re warm and store it until you cool down. Piqué knit fabric structure allows greater airflow and increases moisture wicking through capillary action. Disadvantages: Price - the advanced technology cause the shirt price to be higher than traditional dress shirts	Since this is a fabric the placement spans the whole shirt	Fabric Technology

Type of Ventilation	Company Example	Picture Example	Air Flow Type	Advantages/ Disadvantages	Placement Orientation	Design Type
Sweat Proof Fabric	Smart-Weave		Passive	Advantages: SmartWeave fabric draws perspiration away from the skin, and through a preset route, transports sweat across the shirt's inner surface. The moisture is spread very finely over a large surface area, to dry quickly. Disadvantages: While removing sweat from the skin to keep cool and comfortable this fabric technology doesn't have any true ventilation aspect other then it being 100% cotton which is a breathable fiber	Since this is a fabric the placement spans the whole shirt	Fabric Technology
Spacer Fabric	NCSU College of Textiles		Passive	Advantages: Space fabrics provide airflow between layers to keep the body cool Disadvantages: the three-layer fabric could provide unwanted bulk to the garment	Can be places anywhere; usually shown at top of t-shirts in the upper torso region	Fabric Technology

Appendix B: Ventilated Shirt Design Detailed Breakdown

Design 1: Laser Cut Holes

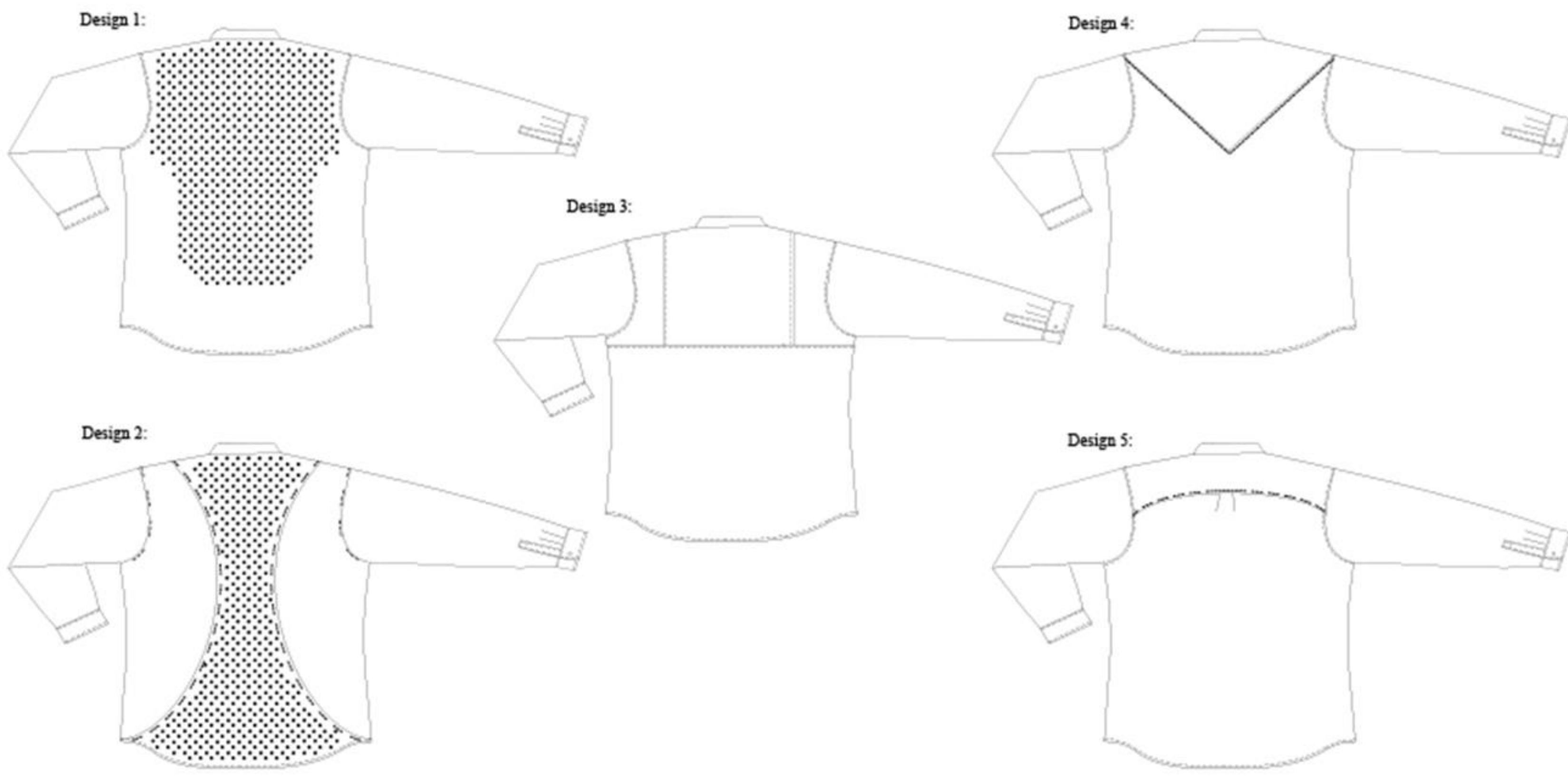
Design 2: Sewn in Back Mesh with Vented Seams

Design 3: Back Vent with a layer of mesh underneath

Design 4: SmartWeave Sweat Proof Back Yoke

Design 5: Vented Back Yoke Seam with a Phase Change

Material Fabric Base



Appendix C: Physical Testing Lab Results – Fabric Thickness Tables

Sample: Cotton Inc. TransDRY® Fabric - Plain		Sample: Cotton Inc. TransDRY® Fabric Design 1 1/8 in hole		Sample: Cotton Inc. TransDRY® Fabric Design 2 1/8 in hole		Sample: Cotton Inc. TransDRY® Fabric Design 3 1/8 in hole		Sample: Cotton Inc. TransDRY® Fabric Design 4 1/8 in hole	
1	0.006	1	0.006	1	0.006	1	0.006	1	0.006
2	0.006	2	0.006	2	0.006	2	0.006	2	0.006
3	0.006	3	0.006	3	0.006	3	0.006	3	0.006
4	0.006	4	0.006	4	0.006	4	0.006	4	0.006
5	0.006	5	0.006	5	0.006	5	0.006	5	0.006
6	0.006	6	0.006	6	0.006	6	0.006	6	0.006
7	0.006	7	0.006	7	0.006	7	0.006	7	0.006
8	0.006	8	0.006	8	0.006	8	0.006	8	0.006
9	0.006	9	0.006	9	0.006	9	0.006	9	0.006
10	0.006	10	0.006	10	0.006	10	0.006	10	0.006
Average: 0.006		Average: 0.006		Average: 0.006		Average: 0.006		Average: 0.006	

Sample: Cotton Inc. TransDRY® Fabric Design 1B 1/16 in hole		Sample: Cotton Inc. TransDRY® Fabric Design 1 1/16 in hole		Sample: Cotton Inc. TransDRY® Fabric Design 2 1/16 in hole		Sample: Cotton Inc. TransDRY® Fabric Design 3 1/16 in hole		Sample: Cotton Inc. TransDRY® Fabric Design 4 1/16 in hole	
1	0.006	1	0.006	1	0.006	1	0.006	1	0.006
2	0.006	2	0.006	2	0.006	2	0.006	2	0.006
3	0.006	3	0.006	3	0.006	3	0.006	3	0.006
4	0.006	4	0.006	4	0.006	4	0.006	4	0.006
5	0.006	5	0.006	5	0.006	5	0.006	5	0.006
6	0.006	6	0.006	6	0.006	6	0.006	6	0.006
7	0.006	7	0.006	7	0.006	7	0.006	7	0.006
8	0.006	8	0.006	8	0.006	8	0.006	8	0.006
9	0.006	9	0.006	9	0.006	9	0.006	9	0.006
10	0.006	10	0.006	10	0.006	10	0.006	10	0.006
Average: 0.006		Average: 0.006		Average: 0.006		Average: 0.006		Average: 0.006	

Sample: Hanesbrands X-Temp Fabric Jersey Knit	
1	0.029
2	0.027
3	0.029
4	0.029
5	0.029
6	0.028
7	0.028
8	0.028
9	0.029
10	0.027
Average Thickness:	
	0.0283

Sample: Control Dress Shirt Woven Fabric	
1	0.01
2	0.011
3	0.01
4	0.01
5	0.01
6	0.011
7	0.01
8	0.011
9	0.011
10	0.01
Average Thickness:	
	0.0104

Appendix D: Physical Testing Lab Results – Air Permeability Tables

Sample: Cotton Inc. TransDRY® Fabric Plain Orifice Size: 8mm		
	Manometer:	CFM:
1	6.1	114
2	5.8	111
3	6	113
4	5.7	110
5	4.6	98.6
6	6.2	115
7	5.4	107
8	4.3	95.2
9	5.6	109
10	5.8	111
	Average CFM:	108.38

Sample: Hanesbrands X-Temp Fabric Jersey Knit Orifice Size: 8mm		
	Manometer:	CFM:
1	9.5	143
2	6	113
3	7.3	125
4	8.3	133
5	8	131
6	8.1	132
7	9.7	144
8	6.4	117
9	9	139
10	6	113
	Average CFM:	129

Sample: Control Dress Shirt Fabric Orifice Size: 8mm		
	Manometer:	CFM:
1	3.5	85.7
2	3.2	81.9
3	3.1	80.7
4	3.6	86.9
5	3.5	85.7
6	3.4	84.4
7	3.1	80.7
8	3.2	81.9
9	3	79.4
10	3.3	83.2
	Average CFM:	83.05

Sample: Cotton Inc. TransDRY® Fabric Design 1 - 1/16 in hole Orifice Size: 11mm		
	Manometer:	CFM:
1	6	216
2	5.8	212
3	6	216
4	5.7	210
5	6	216
6	5.8	212
7	6.1	218
8	5.9	214
9	5.8	212
10	5.7	210
	Average CFM:	213.6

Sample: Cotton Inc. TransDRY® Fabric Design 1 - 1/8 in hole Orifice Size: 16mm		
	Manometer:	CFM:
1	6.7	484
2	6.9	491
3	6.6	481
4	7.6	516
5	7.1	499
6	7.2	502
7	7.3	506
8	7.3	506
9	6.5	477
10	6.2	466
	Average CFM:	492.8

Sample: Cotton Inc. TransDRY® Fabric Design 1B - 1/16 in hole Orifice Size: 11mm		
	Manometer:	CFM:
1	6	216
2	5.9	214
3	6.2	220
4	5.6	208
5	5.9	214
6	6.1	218
7	5.8	212
8	5.9	214
9	5.7	210
10	6.1	218
	Average CFM:	214.4

Sample: Cotton Inc. TransDRY® Fabric Design 2 - 1/16 in hole Orifice Size: 11mm		
	Manometer:	CFM:
1	4.3	182
2	5	197
3	4.5	187
4	4.6	189
5	5.1	199
6	4.8	193
7	5.2	201
8	5.1	199
9	5.4	205
10	5.3	203
	Average CFM:	195.5

Sample: Cotton Inc. TransDRY® Fabric Design 2 - 1/8 in hole Orifice Size: 16mm			
	Manometer:		CFM:
1	4.7		406
2	6.1		463
3	5.1		423
4	5.2		427
5	5		419
6	4.2		383
7	5.5		439
8	5.6		443
9	5.4		435
10	5.2		427
		Average CFM:	426.5

Sample: Cotton Inc. TransDRY® Fabric Design 3 - 1/16 in hole Orifice Size: 8mm		
	Manometer:	CFM:
1	7.6	127
2	7.6	127
3	7.7	128
4	7.9	130
5	7.7	128
6	7.3	125
7	7.5	127
8	7	122
9	7.5	127
10	7.7	128
	Average CFM:	126.9

Sample: Cotton Inc. TransDRY® Fabric Design 3 - 1/8 in hole Orifice Size: 11mm		
	Manometer:	CFM:
1	8.1	252
2	9.1	267
3	9.2	269
4	8.8	263
5	8.1	252
6	8.5	258
7	8.1	252
8	7	234
9	7.5	242
10	7.8	247
	Average CFM:	253.6

Sample: Cotton Inc. TransDRY® Fabric Design 4 - 1/16 in hole Orifice Size: 8mm		
	Manometer:	CFM:
1	8.2	133
2	7.7	128
3	8.3	133
4	8	131
5	8.1	132
6	8.2	133
7	7.8	129
8	8	131
9	8	131
10	8.6	136
	Average CFM:	131.7

Sample: Cotton Inc. TransDRY® Fabric Design 4 - 1/8 in hole Orifice Size: 11mm		
	Manometer:	CFM:
1	5.6	208
2	6.1	218
3	5.8	212
4	6	216
5	7	234
6	6.9	232
7	5.5	207
8	5.7	210
9	5.5	207
10	5.6	208
	Average CFM:	215.2

Appendix E: Full TPACC Thermal Manikin Lab Report

A Report

to

Rachel Godown

on

Thermal and Evaporative Heat Transfer Properties of Three Garment Configurations

from

Textile Protection and Comfort Center (T-PACC)
College of Textiles
North Carolina State University
Raleigh, North Carolina 27695-8301

September 2017

Evaluation of Test Items

Three garment configurations were submitted to the Textile Protection and Comfort Center (TPACC) in the College of Textiles at North Carolina State University. An advanced sweating manikin system was used to determine the thermal and evaporative resistances of this test garment. Test samples were tested at the TPACC testing facility. The purpose of this report is to describe the test methods used to characterize these materials and to present the results of the laboratory tests.

Test Materials

Three garment configuration were tested on the sweating thermal manikin system. The test shirts were tested for thermal resistance and evaporative resistance and identified as test garments **A, B and C**. In addition to the test shirt, the manikin was also dressed in jeans, socks, briefs, and shoes. The test shirt was tucked into the jeans.

Legend:
A: Long sleeve striped shirt
B: Long sleeve yellow vented shirt
C: Short sleeve polo shirt

NCSU Sweating Thermal Manikin System

The NCSU sweating manikin system is a "Newton" type instrument designed to evaluate heat and moisture management properties of clothing systems. This instrument simulates heat and sweat production making it possible to assess the influence of clothing on the thermal comfort process for a given environment. Simultaneous heat and moisture transport through the clothing system, and variations in these properties over different parts of the body can be quantified.

The manikin consists of several features designed to work together to evaluate clothing comfort and/or heat stress. Housed in a climate-controlled chamber (Figure 1), the manikin surface is divided into 34 separate sections, each of which has its own sweating, heating, and temperature measuring system. With the exception of a small portion of the face, the whole manikin surface can continuously sweat.

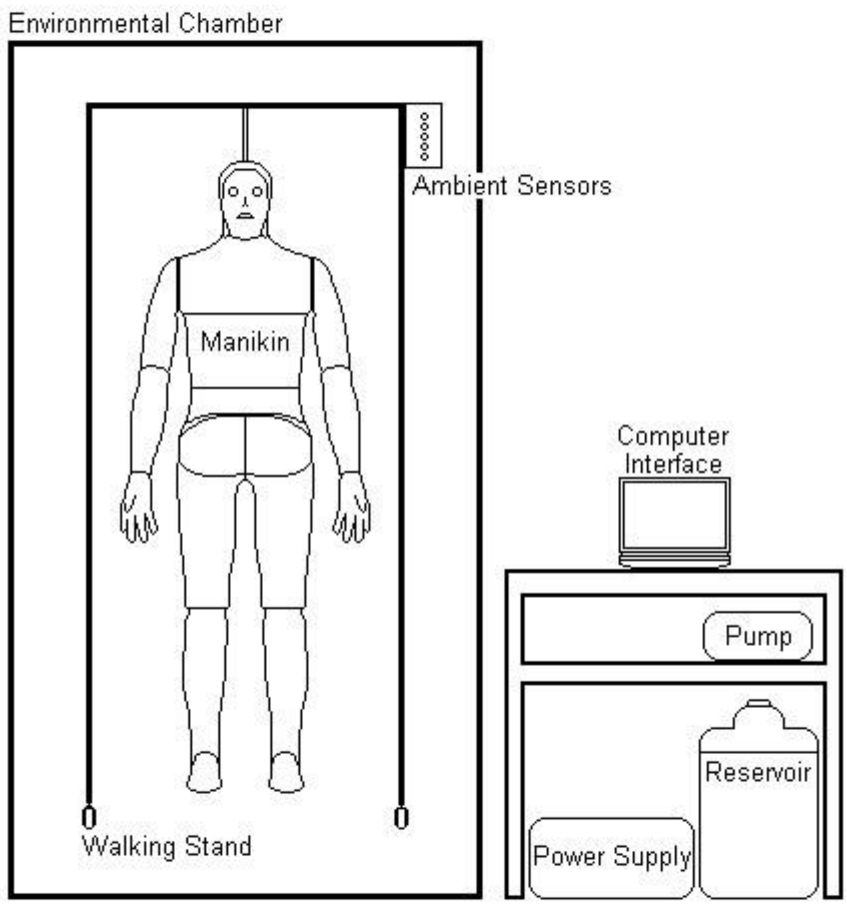


Figure 1. Test Arrangement

Using a pump, preheated water is supplied from a reservoir located outside of the environmental chamber. An internal sweat control system distributes moisture to 139 "sweat glands" distributed across the surface of the manikin. Water supplied to the simulated sweat glands is controlled by operator entry of the desired sweat rate. Each sweat gland is individually calibrated and the calibration values are used by the control software to maintain the sweat rate of each body section.

Water exuding from each simulated sweat gland is absorbed by a custom made body suit. This specialty designed suit acts as the manikin's 'skin' during sweating tests. It is form-fitted to the manikin to eliminate air gaps and provides wicking action to evenly distribute moisture across the entire manikin surface.

Continuous temperature control for the 34 body segments is accomplished by a process control unit that uses analog signal inputs from separate Resistance Temperature Detectors (RTDs). These evenly distributed RTDs are used instead of point sensors because they provide temperature measurements in a manner such that all areas are equally weighted. Distributed over an entire section, each RTD is embedded just below the surface and provides an average temperature for each section. Software establishes any discrepancy between temperature set point and the input signal, and adjusts power to section heaters as needed. Temperature controls are adjustable, by the operator, for each heater control.

Test Protocol

The test ensembles were measured for thermal and evaporative resistance. Thermal resistances of the ensembles were measured according to ASTM F 1291 *Standard Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin*. The evaporative resistances were measured according to ASTM F 2370 *Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin*. Tests for thermal resistance occurred in nonisothermal conditions; tests for evaporative resistance were carried out under isothermal conditions. The testing conditions used are shown in Table 1 and 2. Three repetitions were completed for each garment configuration, as specified by these standards. An additional round of testing was completed after the standard ASTM F 1291 and 2370 tests wherein the manikin was set to a walking speed of 2.5 mph or 55 double steps per minute (dpsm) in the manikin software with a higher wind speed of 0.7 m/s.

Table 1 - Testing Conditions – Thermal Resistance

	Standing	Walking
Air Temperature (°C)	20	20
RH (%)	50	50
Air Speed (m/s)	0.4	0.7
Walking Speed (mph)	0	2.5
Skin Temperature (°C)	35	35

Table 2 - Testing Conditions – Evaporative Resistance

	Standing	Walking
Air Temperature (°C)	35	35
RH (%)	40	40
Air Speed (m/s)	0.4	0.7
Walking Speed (mph)	0	2.5
Skin Temperature (°C)	35	35

Thermal and evaporative resistance measurements were taken from all sections (Full Body), the zones covered by the long sleeve shirt (Long Sleeve Zones), and the zones covered by the short sleeve shirt (Short Sleeve Zones).

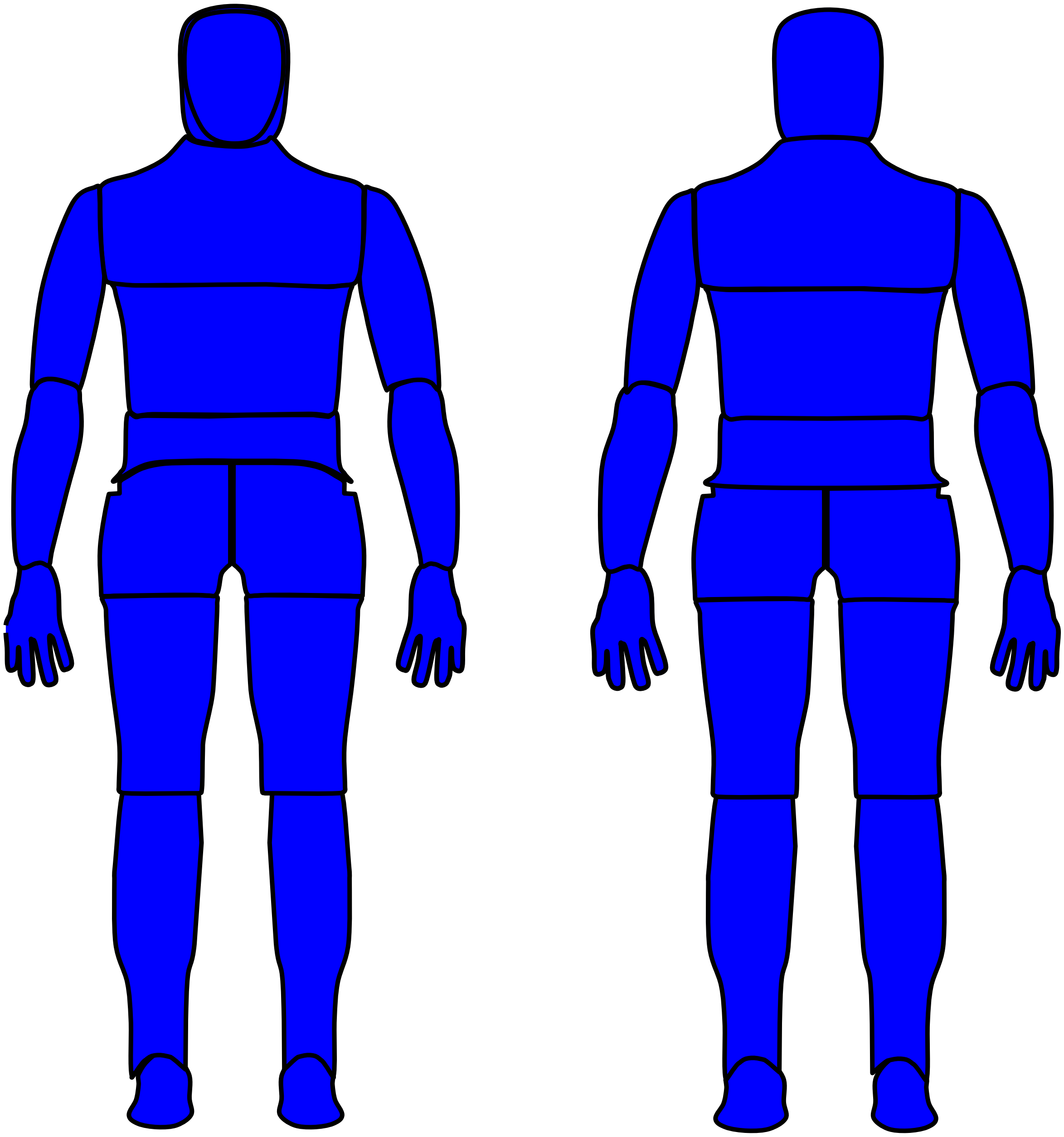


Figure 2. Body Sections Evaluated for Full Body (Blue Sections)

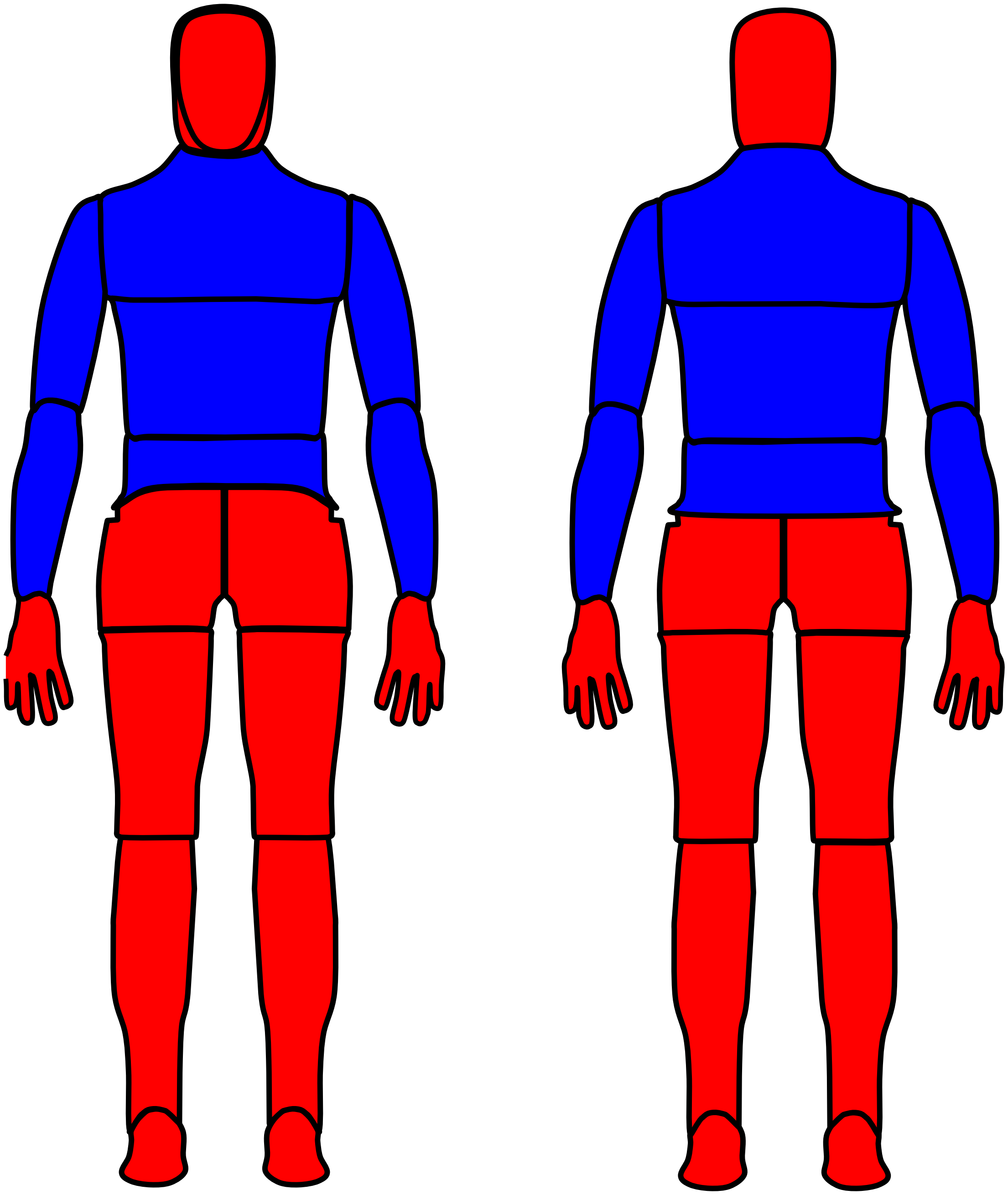


Figure 3. Body Sections Evaluated for Long Sleeve Shirt Zones (Blue Sections)

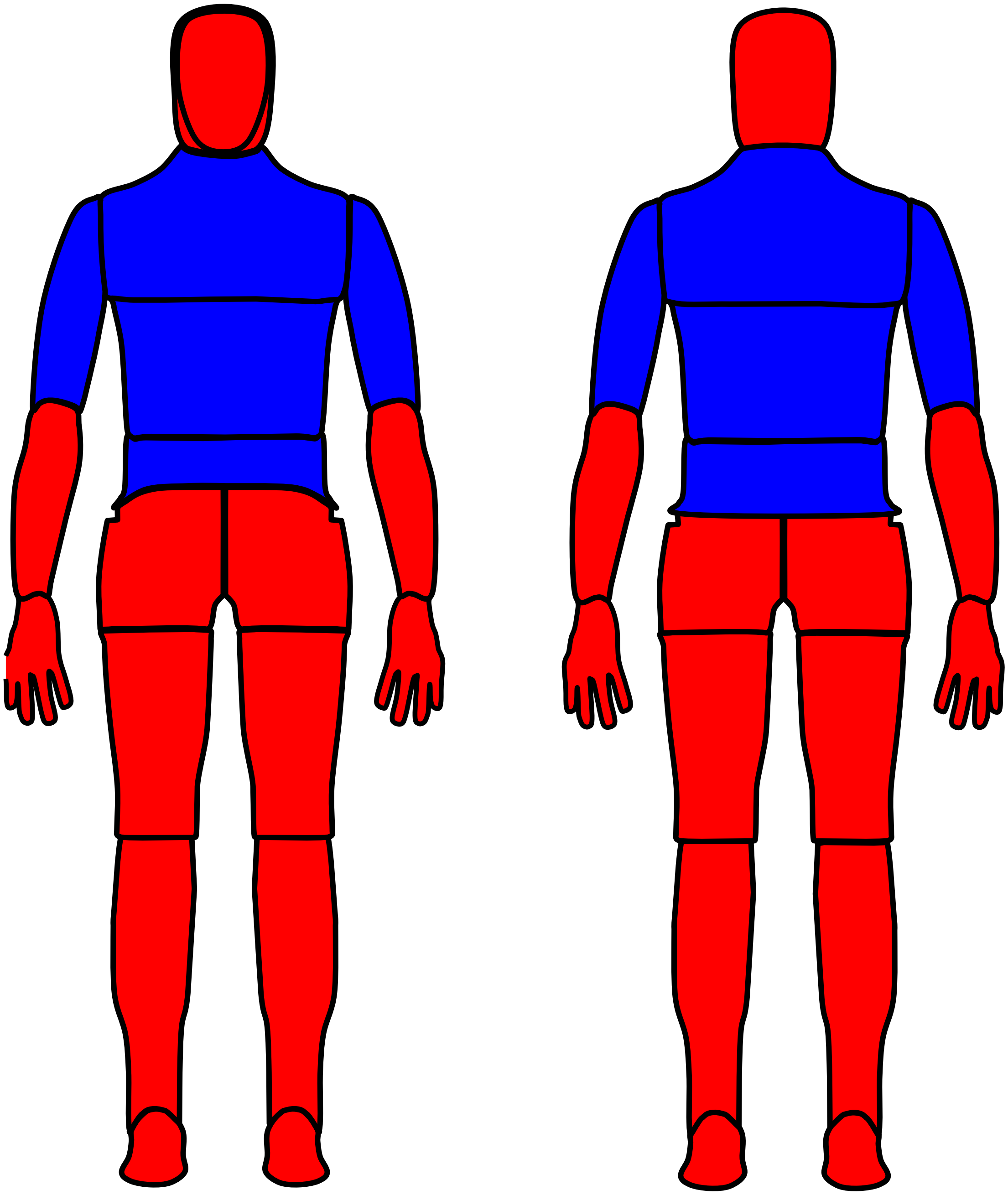


Figure 4. Body Sections Evaluated for Short Sleeve Shirt Zones (Blue Sections)

Measurement Option 1 in the ASTM F 2370 standard was used for all evaporative resistance measurements. Thermal resistance values were converted to units of clo and evaporative resistance values were converted to permeability index values. Both sets of units are reported since either one may be commonly used. The reported parameters are listed and described below.

See Appendix A for equations and conversions.

Dry and Sweating Skin Tests

The measurement of heat transfer is a measure of heat flow from the manikin surface (heated to a skin surface temperature of 35 ^{o}C) through an ensemble into the test environment and is determined for both simulated dry and wet skin conditions. Heat loss parameters, calculated from thermal transport measurements, include:

a. **Total Thermal Resistance (R_t)** [$^{o}C \cdot m^2/W$], total thermal resistance (insulation) provided by the manikin, garment ensemble, and air layers.

b. **Total Evaporative Resistance (R_{et})**, [$kPa \cdot m^2/W$], total evaporative resistance provided by the manikin, garment ensemble, and air layers.

c. **Intrinsic Thermal Resistance (R_{cl})**, [$^{o}C \cdot m^2/W$], total thermal resistance provided by the garment ensemble only.

d. **Intrinsic Evaporative Resistance (R_{ecl})**, [$kPa \cdot m^2/W$], intrinsic evaporative resistance provided by the garment ensemble only.

e. **Total Insulation Value (I_t)**, [clo], total insulation provided by the manikin, garment ensemble, and air layers expressed in units of clo. Clo is a unit of thermal resistance which indicates the insulating ability of the test material. Materials having higher clo values provide wearers with more thermal insulation. A clo value of 1 represents a typical man's business suit and is expected to maintain thermal comfort for a person in a normal indoor environment. Typical requirements vary from about 0.5 clo for summer wear to 4 to 5 clo for outdoor winter clothing.

Other useful heat loss parameters calculated from thermal transport measurements but not defined in the ASTM F1291 or ASTM F2370 standards include:

f. The **i_m value**, or permeability index, indicates moisture-heat permeability through the material on a scale of 0 (totally impermeable) to 1 (totally permeable) normalized for the permeability of still air (naked skin). This comfort parameter indicates the effect of skin moisture on heat loss as in the case of a sweating skin condition.

g. **Predicted Heat Loss Potential ($Q_{predicted, T, RH}$) [**W/m^2], gives a predicted level of the total amount of heat that could be transferred from the manikin to the ambient environment for a specified condition. It uses the thermal and evaporative resistance values to calculate predicted levels of evaporative and dry heat transfer components for a specific environmental condition. In this case the specified environment is 25°C, 65% RH. The overall $Q_{predicted\ 25C,\ 65RH}$ is calculated by adding the predicted dry component of heat loss to the predicted evaporative component of heat loss and reflects the predicted total amount of heat loss possible in a 25°C, 65% RH environment.

Test Results

The average values of Full Body Zones for R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ are reported in Table 1. The average values of Partial Zones for R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted,}$
$25_{C, 65RH}$ are reported in Table 2.

Table 1 - Average R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for Full Body Zones - Standing

Ensemble	R_t	R_{et}	Rcl	Recl	It	im	$Q_{predicted, 25C, 65RH*}$
A	**0.1637**	**0.02330**	**0.1011**	**0.01336**	**1.06**	**0.43**	**214.3**
B	**0.1614**	**0.02222**	**0.0987**	**0.01232**	**1.04**	**0.44**	**222.6**
C	**0.1432**	**0.02119**	**0.0807**	**0.01139**	**0.92**	**0.41**	**238.2**

Table 2 - Average R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for Long Sleeve Shirt Zones - Standing

Ensemble	R_t	R_{et}	Rcl	Recl	It	im	Qpredicted, 25C, 65RH*
A	**0.1775**	**0.02361**	**0.1155**	**0.01345**	**1.14**	**0.46**	**207.4**
B	**0.1671**	**0.02112**	**0.1051**	**0.01100**	**1.08**	**0.48**	**229.0**
C	**0.1341**	**0.01817**	**0.0722**	**0.00816**	**0.86**	**0.45**	**271.0**

Table 3 - Average R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for Short Sleeve Shirt Zones - Standing

Ensemble	R_t	R_{et}	Rcl	Recl	It	im	Qpredicted, 25C, 65RH*
A	**0.1827**	**0.02483**	**0.1195**	**0.01401**	**1.18**	**0.45**	**198.5**
B	**0.1709**	**0.02231**	**0.1076**	**0.01154**	**1.10**	**0.47**	**218.6**
C	**0.1690**	**0.02288**	**0.1058**	**0.01222**	**1.09**	**0.45**	**215.1**

Table 4 - Average R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for Full Body Zones - Walking

Ensemble	R_t	R_{et}	Rcl	Recl	It	im	Qpredicted, 25C, 65RH*
A	**0.1054**	**0.01225**	**0.0595**	**0.00593**	**0.68**	**0.53**	**386.1**
B	**0.1125**	**0.01182**	**0.0666**	**0.00558**	**0.73**	**0.58**	**390.5**
C	**0.0933**	**0.01201**	**0.0476**	**0.00578**	**0.60**	**0.47**	**404.3**

Table 5 - Average R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for Long Sleeve Shirt Zones - Walking

Ensemble	R_t	R_{et}	Rcl	Recl	It	im	Qpredicted, 25C, 65RH*
A	**0.1187**	**0.01300**	**0.0690**	**0.00541**	**0.77**	**0.56**	**358.5**
B	**0.1116**	**0.01164**	**0.0619**	**0.00412**	**0.72**	**0.58**	**396.2**
C	**0.0880**	**0.01173**	**0.0386**	**0.00424**	**0.57**	**0.46**	**417.7**

Table 6 - Average R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for Short Sleeve Shirt Zones - Walking

Ensemble	R_t	R_{et}	Rcl	Recl	It	im	Qpredicted, 25C, 65RH*
A	**0.1190**	**0.01357**	**0.0661**	**0.00494**	**0.77**	**0.54**	**346.8**
B	**0.1130**	**0.01202**	**0.0601**	**0.00349**	**0.73**	**0.57**	**385.2**
C	**0.1146**	**0.01396**	**0.0620**	**0.00545**	**0.74**	**0.50**	**342.7**

* $Q_{predicted, 25C, 65RH}$ is the predicted total heat loss from dry and evaporative heat transfer for a 25°C, 65% RH environment consistent with the standard ASTM F1868 THL environment

Appendix B includes a visual representation of the average predicted heat loss for each individual section of the manikin for each test ensemble.

The thermal resistance of the air layer around the nude manikin in standing conditions was measured to be 0.07335□C·m^2/W. The evaporative resistance of the air layer around the nude manikin in standing conditions was measured to be 0.01256 kPa·m^2/W.

The thermal resistance of the air layer around the nude manikin in walking conditions was measured to be 0.06149□C·m^2/W. The evaporative resistance of the air layer around the nude manikin in walking conditions was measured to be 0.01004 kPa·m^2/W.

A clothing factor of 1.17 was used for this test configuration. These clothing factors were estimated using "TABLE 1 Clothing Area Factors (f_{cl}) for Typical Protective Clothing" found in
ASTM F 1291 *Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin*. A copy of the table can be found in Appendix C.

Caveat

These data, obtained under controlled laboratory conditions, characterize the thermal and evaporative resistance values of test garment responses to specific environmental conditions. These results should not be used to appraise the safety benefits or risks of the materials, products, or assemblies in extreme use conditions. The relationships between laboratory tests and field performance are not simple, and many things must be considered when making practical translations. Clothing comfort and heat stress performance are determined by many factors including the gear worn, activity level, and the environmental conditions of use. These results do not address the full range of these issues. It is not our intention to recommend, exclude, or predict the suitability of any commercial product for a particular end use.

Appendix A: Calculation of Heat Transfer Parameters

Vapor pressure calculations

All vapor pressures are calculated from temperature and relative humidity based on Wexler's formulation according to the following calculations:

e_s = saturation vapor pressure (mb)

$$e_s = a_1 + a_2(T-T_0) + a_3(T-T_0)^2 + a_4(T-T_0)^3 + a_5(T-T_0)^4 + a_6(T-T_0)^5 + a_7(T-T_0)^6$$

$a_1 – a_7$ = Coefficients of the sixth order polynomial fits to SVP (See Appendix D)
T = temperature (K)
T_0 = 273.15

P = water vapor pressure (kPa)

$$P = [(RH*e_s)/100]/10$$

RH = relative humidity (%)
e_s = saturation vapor pressure (mb)

Calculation of total thermal and evaporative resistance values

R_t = total thermal resistance of clothing and surface air layer (total thermal resistance of surface air layer only if nude) (□C·m^2/W)

$$R_t = \frac{(Ts - Ta) \cdot A}{H}$$

H = power input for the insulation testing (dry) condition (W)
Ts = Temperature of the manikin surface (□C)
Ta = Temperature in the local environment (□C)
A = area of the manikin being evaluated (m^2)
W = power input (W)

R_{et} = total evaporative resistance of the clothing and surface air layer (total evaporative resistance of surface air layer only if nude) (kPa·m^2/W)

$$R_{et} = [(P_s - P_a) \cdot A] / [H_e - (T_s - T_a) \cdot A/R_{ct}]$$

Ps = water vapor pressure at the surface of the manikin (kPa)

Pa = water vapor pressure in the local environment (kPa)

A = area of the manikin being evaluated (1.81 m^2)
H_e = power input for the evaporative testing (wet) condition (W)
Ts = temperature at the manikin surface (°C)
Ta = temperature at the local environment (°C)
R_t = total thermal resistance of the specimen and surface air layer (°C·m^2/W)

Calculation of intrinsic thermal and evaporative resistance values

R_{cl} = intrinsic thermal resistance of the clothing ensemble (°C·m^2/W)

$$Rcl = Rt - Ra/fcl$$

R_t = total thermal resistance of the clothing ensemble and surface air layer (°C·m^2/W) R_a = thermal resistance of the air layer on the surface of the nude manikin (°C·m^2/W) f_{cl} = clothing area factor (dimensionless)

R_{ecl} = intrinsic evaporative resistance of the clothing ensemble (kPa·m^2/W)

$$Recl = Ret - Rea/fcl$$

R_{et} = total evaporative resistance of the clothing ensemble and surface air layer (kPa·m^2/W)

Rea = evaporative resistance of the air layer on the surface of the nude manikin's sweating surface (kPa·m^2/W)
f_{cl} = clothing area factor (dimensionless)

Calculation of I_t and i_m

I_t values are calculated using total thermal resistance values, from the following formula:

$$I_t \text{ (clo)} = R_t / 0.155$$

The i_m value (permeability index) is calculated, using total thermal resistance and total evaporative resistance values, from the following formula:

$$i_m = 0.061 * (R_t/R_{et})$$

Calculation of Predicted Heat Loss Potential

Predicted Heat Loss Potential values are calculated using the total thermal resistance values and total apparent evaporative resistance values, from the following formulas:

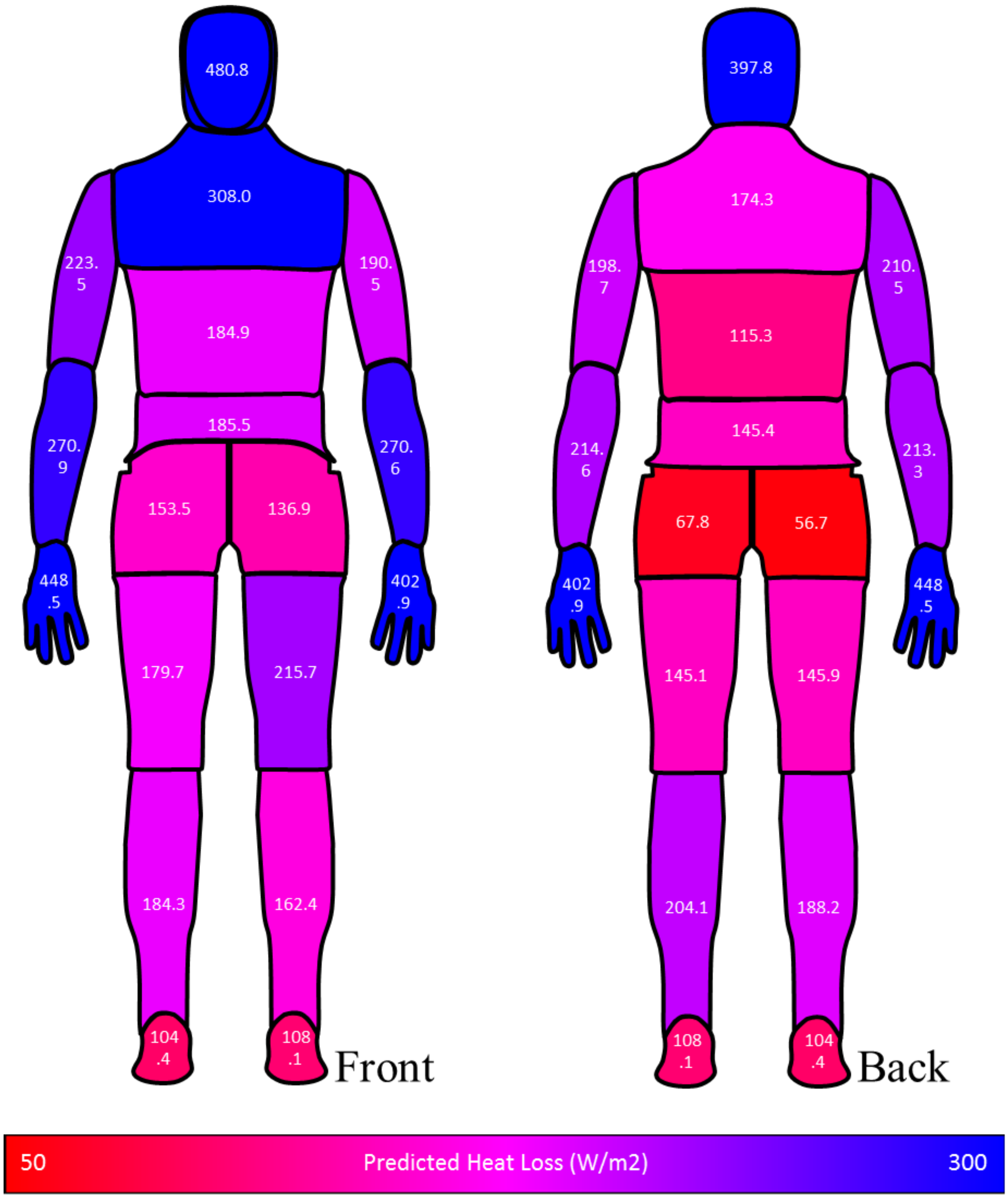
$$Q_{predicted,\ T,\ RH} = [(P_s - P_a) / R_{et}] + [(T_s - T_a) / R_t]$$

T = specified temperature condition
RH = specified relative humidity
Ps = calculated water vapor pressure at the surface of the manikin (kPa)
Pa = calculated water vapor pressure in the specified local environment (kPa)

A = area of the manikin being evaluated (m^2)
$Q_{predicted, T, RH}$ = Predicted HLP for specified environmental conditions (W/m^2)
Ts = specified temperature at the manikin surface (°C)
Ta = specified temperature at the local environment (°C)
R_{et} = total evaporative resistance of the specimen and surface air layer ($kPa \cdot m^2/W$)
R_t = total thermal resistance of the specimen and surface air layer ($°C \cdot m^2/W$)

Appendix B: Individual Thermal and Evaporative Resistance Values Average Heat Losses of Test Ensembles for Individual Manikin Zones

Sample A



Sample A – Standing

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample A –** Full Body - Standing

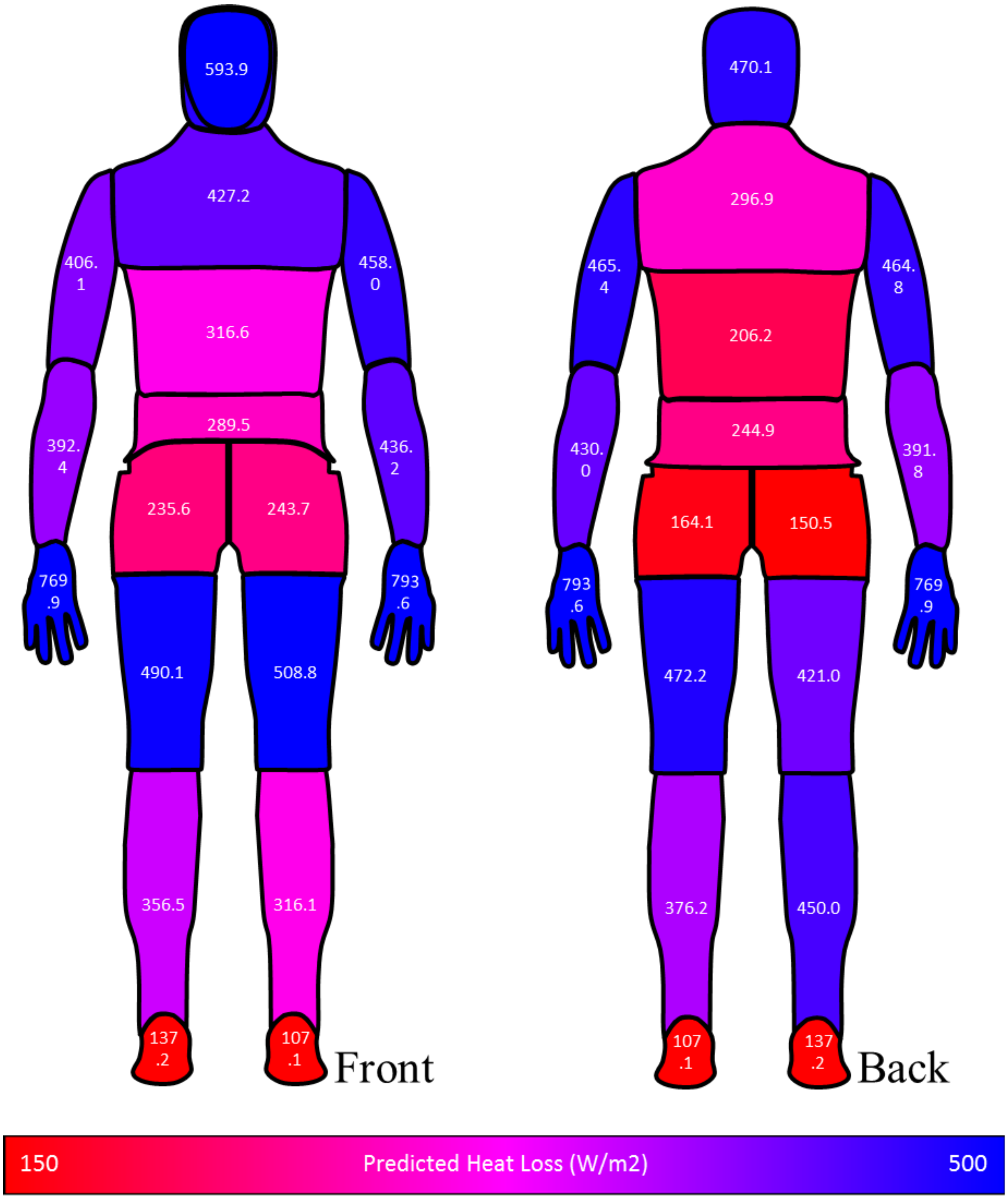
Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1624	0.02328	0.0998	0.01334	1.05	0.43	214.3
2	0.1657	0.02409	0.1031	0.01416	1.07	0.42	209.1
3	0.1630	0.02252	0.1004	0.01258	1.05	0.44	219.5
AVG	**0.1637**	**0.02330**	**0.1011**	**0.01336**	**1.06**	**0.43**	**214.3**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample A –** Long Sleeve Shirt Zones - Standing

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1760	0.02344	0.1141	0.01328	1.14	0.46	208.5
2	0.1794	0.02410	0.1175	0.01394	1.16	0.45	204.3
3	0.1769	0.02330	0.1150	0.01314	1.14	0.46	209.4
AVG	**0.1775**	**0.02361**	**0.1155**	**0.01345**	**1.14**	**0.46**	**207.4**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample A –** Short Sleeve Shirt Zones - Standing

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1802	0.02507	0.1170	0.01425	1.16	0.44	197.0
2	0.1840	0.02533	0.1207	0.01451	1.19	0.44	195.5
3	0.1840	0.02408	0.1208	0.01326	1.19	0.47	202.8
AVG	**0.1827**	**0.02483**	**0.1195**	**0.01401**	**1.18**	**0.45**	**198.5**



Sample A – Walking

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample A** – Full Body - Walking

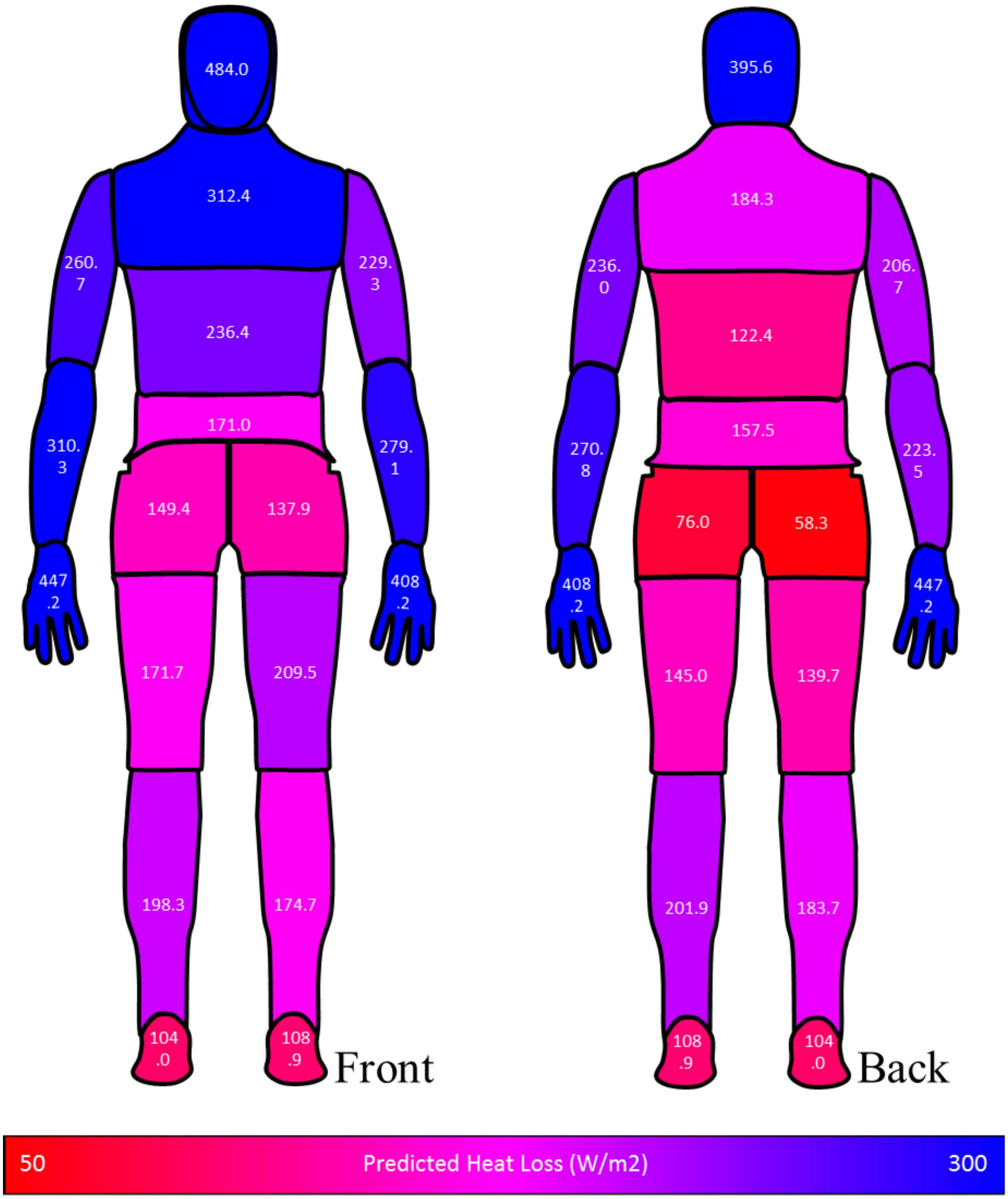
Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1043	0.01240	0.0584	0.00609	0.67	0.51	382.4
2	0.1060	0.01220	0.0601	0.00589	0.68	0.53	387.1
3	0.1059	0.01213	0.0600	0.00582	0.68	0.53	388.8
AVG	**0.1054**	**0.01225**	**0.0595**	**0.00593**	**0.68**	**0.53**	**386.1**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample A** – Long Sleeve Shirt Zones - Walking

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1167	0.01309	0.0670	0.00549	0.75	0.54	356.8
2	0.1198	0.01301	0.0701	0.00541	0.77	0.56	358.4
3	0.1195	0.01291	0.0698	0.00532	0.77	0.56	360.4
AVG	**0.1187**	**0.01300**	**0.0690**	**0.00541**	**0.77**	**0.56**	**358.5**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample A** – Short Sleeve Shirt Zones - Walking

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1167	0.01366	0.0638	0.00503	0.75	0.52	345.1
2	0.1203	0.01358	0.0673	0.00495	0.78	0.54	346.7
3	0.1201	0.01347	0.0672	0.00485	0.77	0.54	348.7
AVG	**0.1190**	**0.01357**	**0.0661**	**0.00494**	**0.77**	**0.54**	**346.8**



Sample B - Standing

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample B –** Full Body - Standing

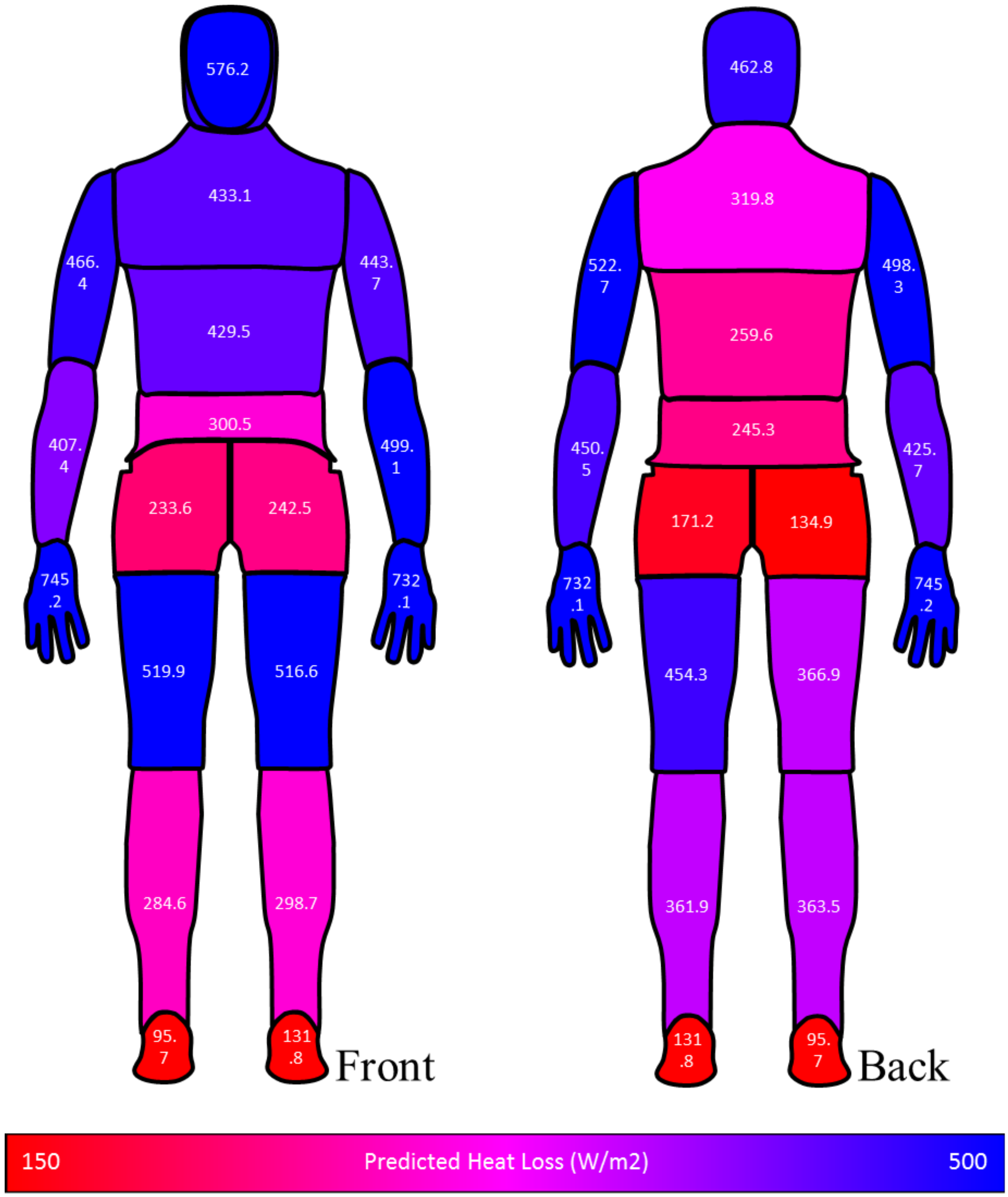
Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1618	0.02144	0.0992	0.01154	1.04	0.46	228.3
2	0.1614	0.02225	0.0987	0.01236	1.04	0.44	222.2
3	0.1608	0.02297	0.0982	0.01307	1.04	0.43	217.2
AVG	**0.1614**	**0.02222**	**0.0987**	**0.01232**	**1.04**	**0.44**	**222.6**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample B –** Long Sleeve Shirt Zones - Standing

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1679	0.02007	0.1059	0.00995	1.08	0.51	237.6
2	0.1676	0.02106	0.1055	0.01094	1.08	0.49	229.2
3	0.1659	0.02223	0.1039	0.01211	1.07	0.46	220.3
AVG	**0.1671**	**0.02112**	**0.1051**	**0.01100**	**1.08**	**0.48**	**229.0**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample B –** Short Sleeve Shirt Zones - Standing

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1730	0.02134	0.1097	0.01056	1.12	0.49	225.6
2	0.1707	0.02204	0.1074	0.01127	1.10	0.47	220.3
3	0.1691	0.02356	0.1058	0.01278	1.09	0.44	209.9
AVG	**0.1709**	**0.02231**	**0.1076**	**0.01154**	**1.10**	**0.47**	**218.6**



Sample B – Walking

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted,\ 25C,\ 65RH}$ for **Sample B –** Full Body - Walking

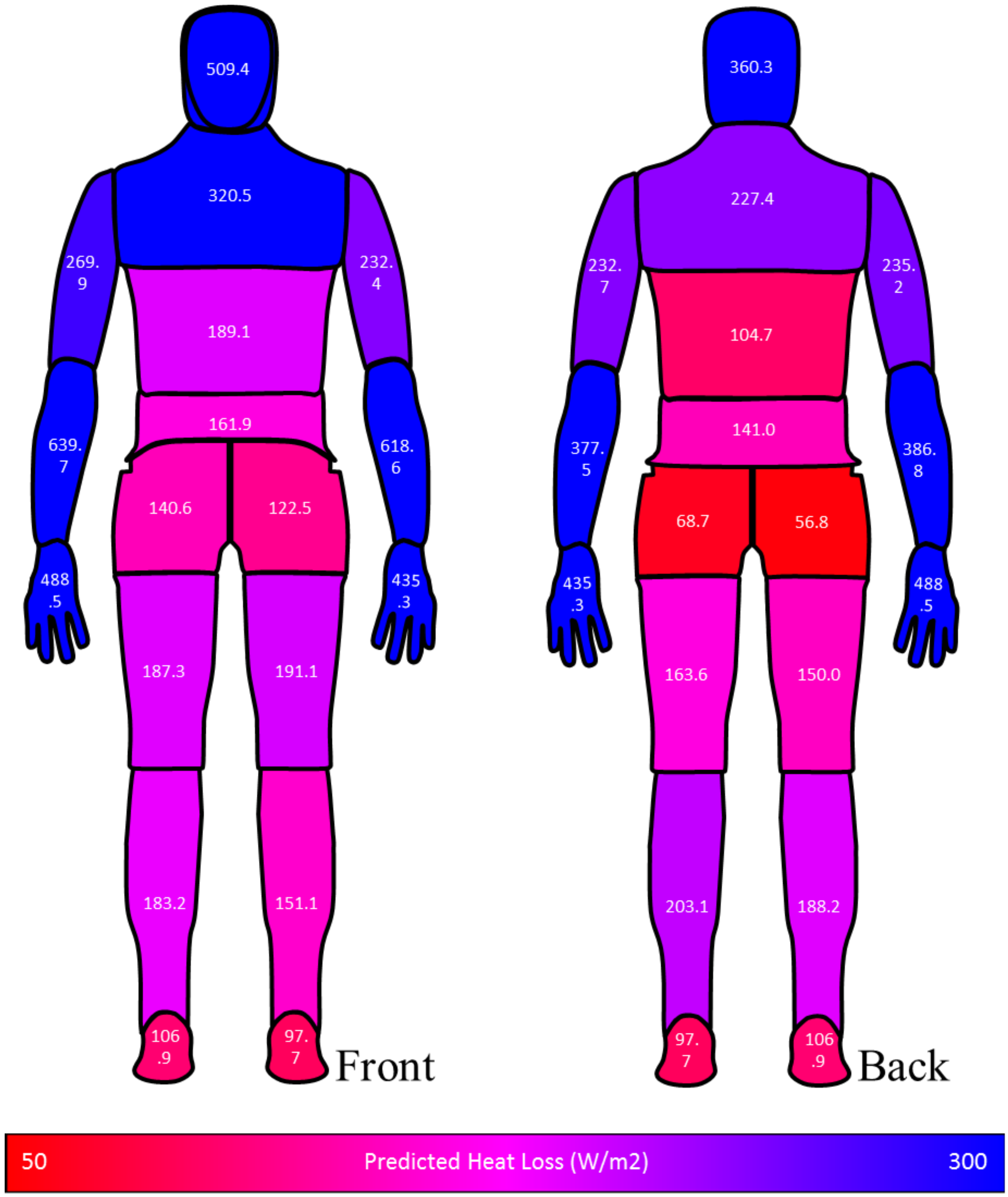
Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1133	0.01191	0.0673	0.00567	0.73	0.58	388.3
2	0.1123	0.01180	0.0663	0.00556	0.72	0.58	391.2
3	0.1121	0.01176	0.0661	0.00552	0.72	0.58	392.1
AVG	**0.1125**	**0.01182**	**0.0666**	**0.00558**	**0.73**	**0.58**	**390.5**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted,\ 25C,\ 65RH}$ for **Sample B –** Long Sleeve Shirt Zones - Walking

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1119	0.01176	0.0622	0.00425	0.72	0.58	392.9
2	0.1114	0.01162	0.0617	0.00411	0.72	0.58	396.6
3	0.1114	0.01153	0.0617	0.00402	0.72	0.59	399.0
AVG	**0.1116**	**0.01164**	**0.0619**	**0.00412**	**0.72**	**0.58**	**396.2**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted,\ 25C,\ 65RH}$ for **Sample B –** Short Sleeve Shirt Zones - Walking

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1134	0.01218	0.0604	0.00365	0.73	0.57	381.4
2	0.1128	0.01200	0.0599	0.00347	0.73	0.57	385.7
3	0.1128	0.01189	0.0599	0.00336	0.73	0.58	388.6
AVG	**0.1130**	**0.01202**	**0.0601**	**0.00349**	**0.73**	**0.57**	**385.2**



Sample C- Standing

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample C –** Full Body - Standing

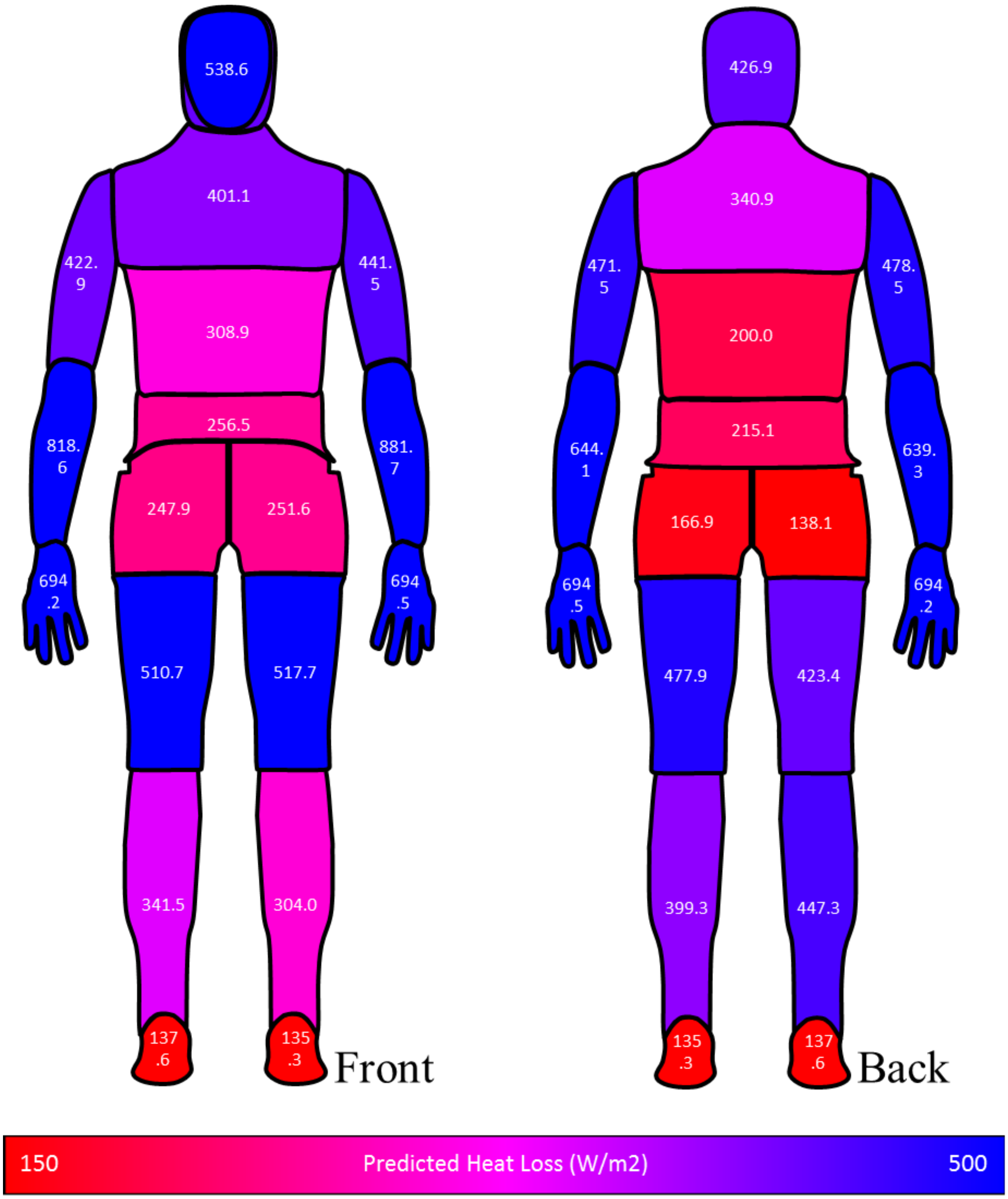
Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1445	0.02169	0.0819	0.01190	0.93	0.41	234.2
2	0.1427	0.02073	0.0801	0.01093	0.92	0.42	241.9
3	0.1426	0.02114	0.0800	0.01134	0.92	0.41	238.5
AVG	**0.1432**	**0.02119**	**0.0807**	**0.01139**	**0.92**	**0.41**	**238.2**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample C –** Long Sleeve Shirt Zones - Standing

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1332	0.01873	0.0713	0.00871	0.86	0.43	265.0
2	0.1343	0.01782	0.0724	0.00781	0.87	0.46	274.7
3	0.1347	0.01796	0.0728	0.00795	0.87	0.46	273.1
AVG	**0.1341**	**0.01817**	**0.0722**	**0.00816**	**0.86**	**0.45**	**271.0**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample C –** Short Sleeve Shirt Zones - Standing

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1664	0.02345	0.1032	0.01278	1.07	0.43	211.3
2	0.1698	0.02297	0.1067	0.01231	1.10	0.45	214.4
3	0.1707	0.02223	0.1075	0.01157	1.10	0.47	219.6
AVG	**0.1690**	**0.02288**	**0.1058**	**0.01222**	**1.09**	**0.45**	**215.1**



Sample C – Walking

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample C –** Full Body - Walking

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.0914	0.01209	0.0458	0.00586	0.59	0.46	402.3
2	0.0935	0.01199	0.0479	0.00577	0.60	0.48	404.6
3	0.0948	0.01194	0.0492	0.00571	0.61	0.48	406.0
AVG	**0.0933**	**0.01201**	**0.0476**	**0.00578**	**0.60**	**0.47**	**404.3**

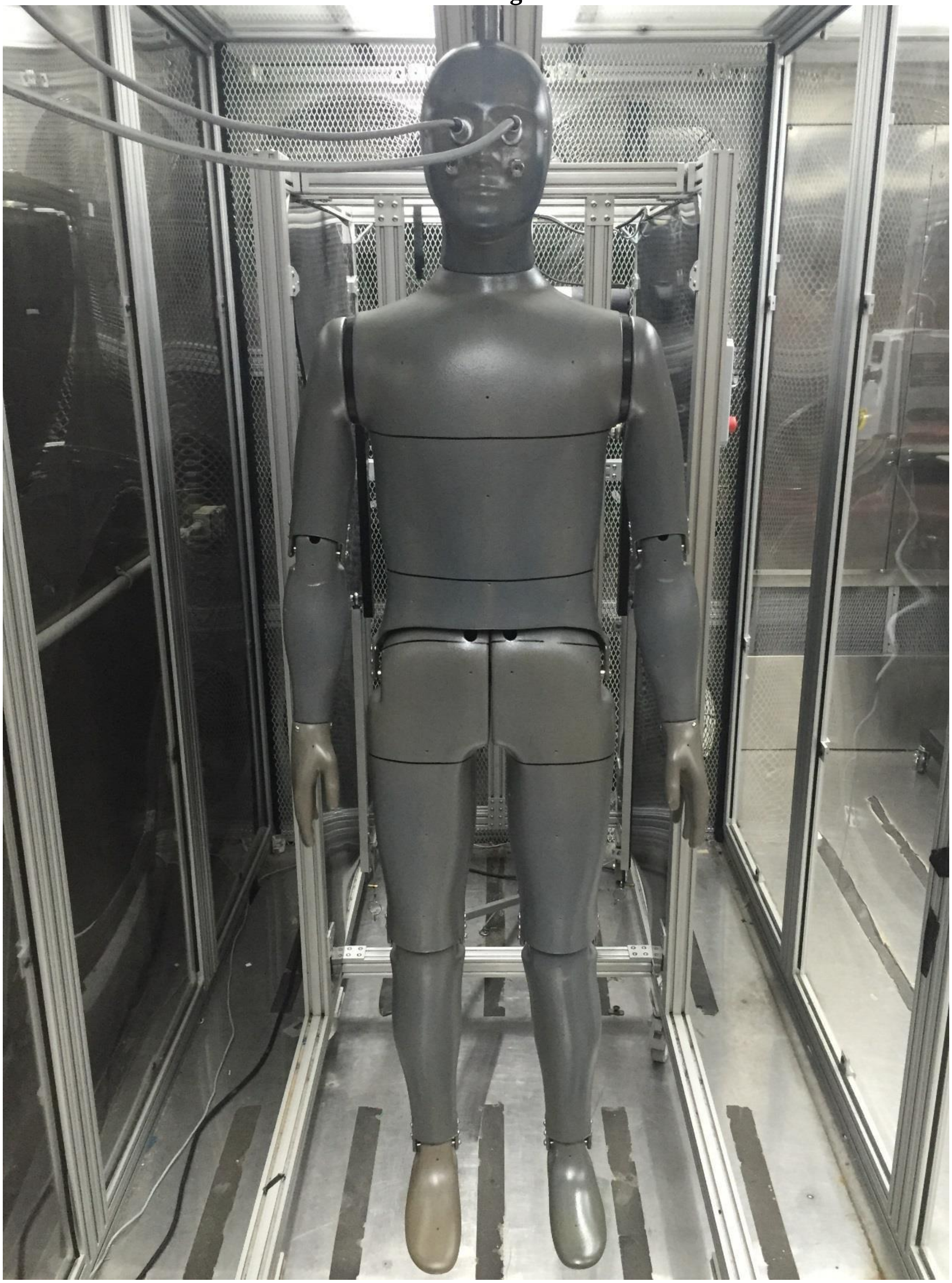
R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample C –** Long Sleeve Shirt Zones - Walking

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.0858	0.01189	0.0365	0.00439	0.55	0.44	413.7
2	0.0884	0.01170	0.0391	0.00421	0.57	0.46	418.4
3	0.0897	0.01160	0.0403	0.00411	0.58	0.47	421.1
AVG	**0.0880**	**0.01173**	**0.0386**	**0.00424**	**0.57**	**0.46**	**417.7**

R_t, R_{et}, R_{cl}, R_{ecl}, I_t, i_m, and $Q_{predicted, 25C, 65RH}$ for **Sample C –** Short Sleeve Shirt Zones - Walking

Rep	R_t	R_{et}	R_{cl}	R_{ecl}	I_t	i_m	$Q_{predicted}$
1	0.1103	0.01417	0.0577	0.00566	0.71	0.47	338.9
2	0.1153	0.01395	0.0627	0.00544	0.74	0.50	343.0
3	0.1182	0.01377	0.0656	0.00526	0.76	0.52	346.2
AVG	**0.1146**	**0.01396**	**0.0620**	**0.00545**	**0.74**	**0.50**	**342.7**

Test Images

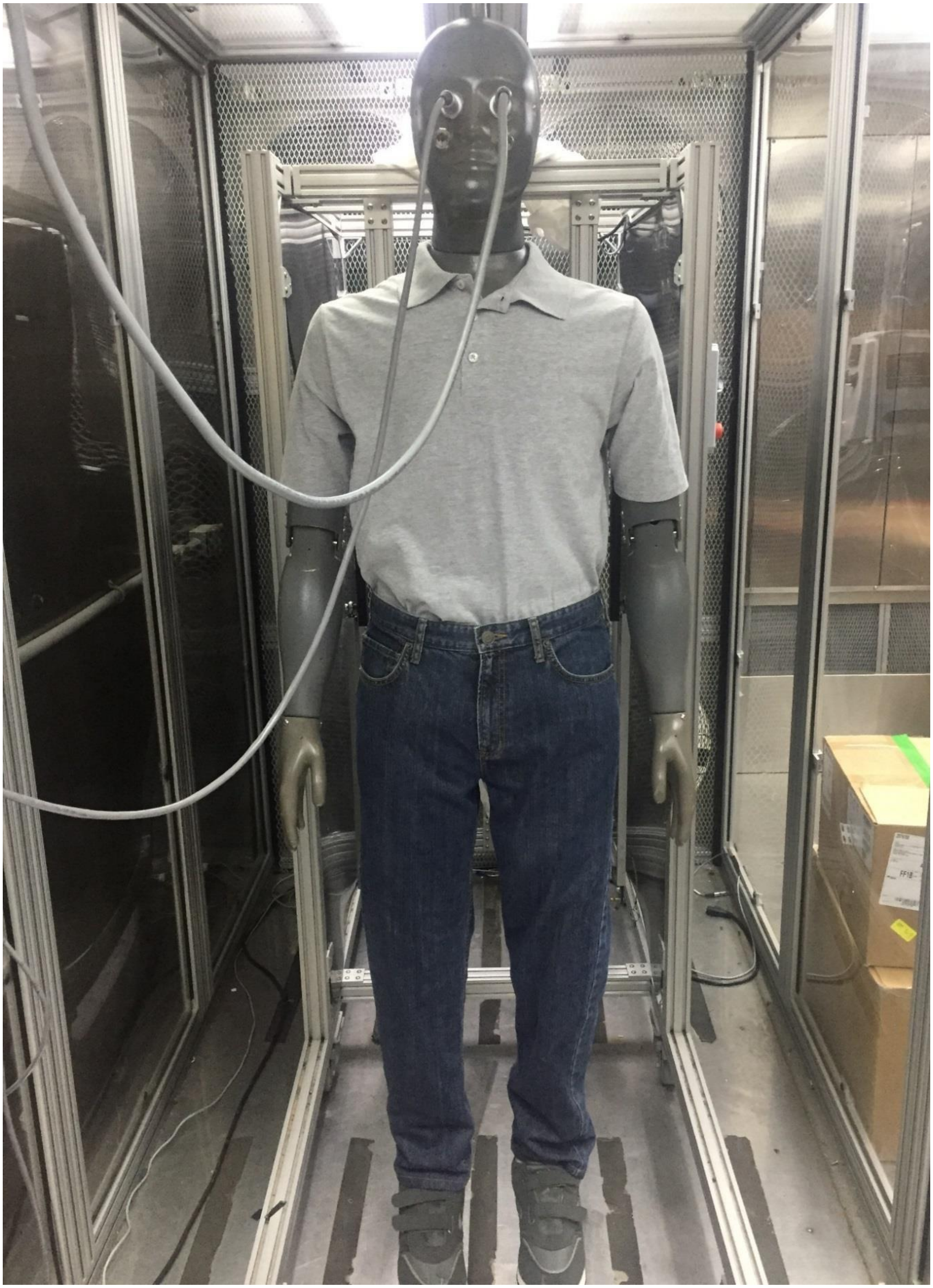


Bare Manikin

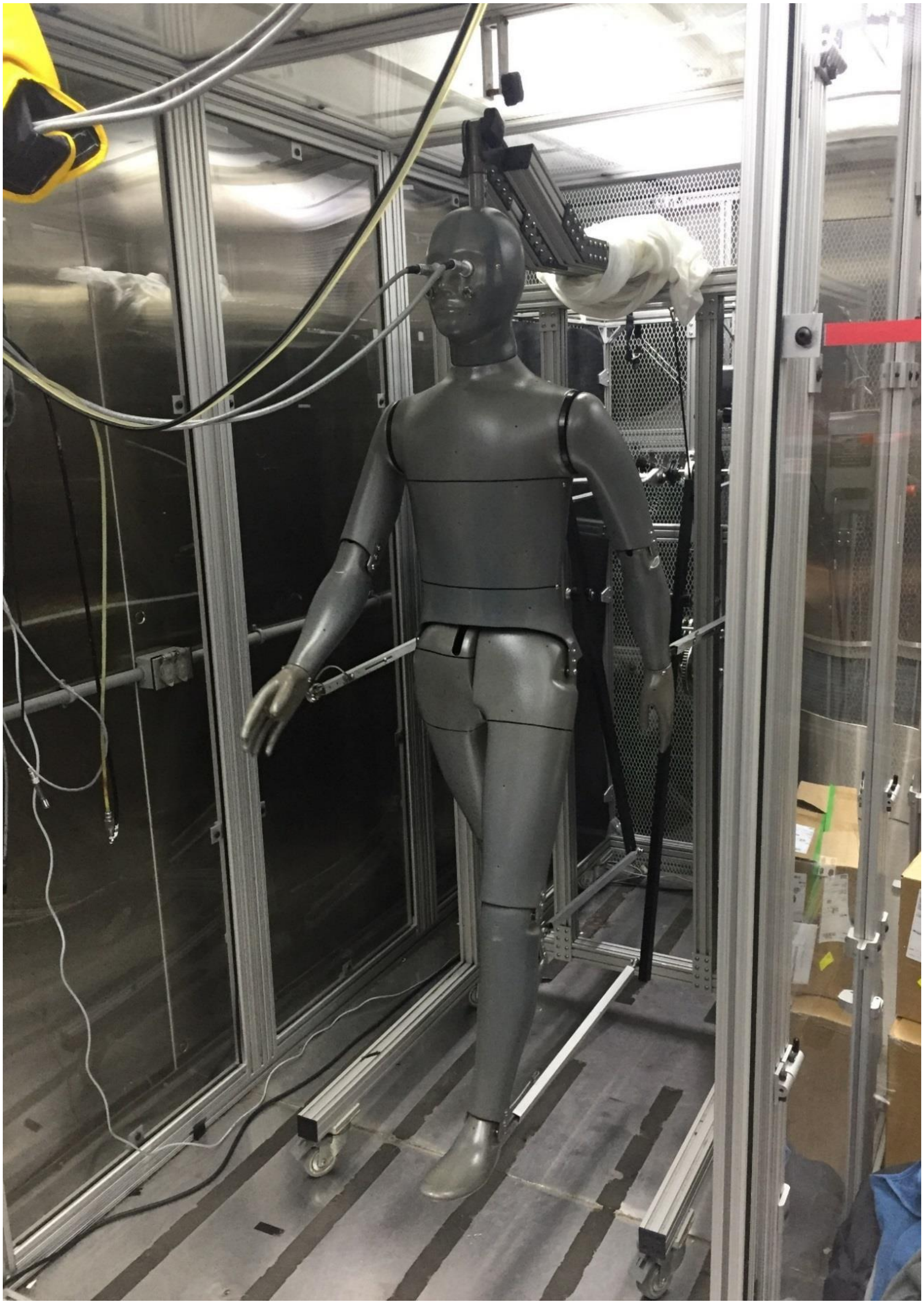
Test Garment A

Test Garment B

Test Garment B (Back View)



Test Garment C



Bare Manikin Walking

jTest Garment A Walking

Appendix C: TABLE 1 Clothing Area Factors (f_{cl}) for Typical Protective Clothing [2]

Ensemble Description f_{cl}	Ensemble Description f_{cl}	f_{cl}
1. Warm Weather Indoor Clothing (Base ensemble)	Short-sleeve shirt, Men's underwear briefs, Khaki pants, Belt, Socks, Athletic Shoes	1.17
2. Cold Weather (Outdoor) Clothing	Base ensemble, Knit hat, Fiberfill jacket, Knit mittens	1.34
3. Chemical Protective Level B Ensemble	Base ensemble, Chemical protective hood, Chemical protective jacket, Chemical protective gloves, Belt, Chemical protective pants	1.60
4. Surgical Ensemble	Men's underwear briefs, Bouffant cap, Surgical mask, Scrub shirt, Scrub pants, Surgical gown, Surgical gloves, Socks, Athletic shoes, Shoe Covers	1.36
5. Cold Weather Expedition Ensemble	Thermal underwear (top and bottom), Cold Weather Expedition Suit, Fiberfill mittens, Men's underwear briefs, Socks, Work boots	1.48
6. Flame Resistant Protective Clothing (calibration ensemble)	Flame resistant long sleeve shirt, Men's underwear briefs, Flame resistant pants, Socks, Athletic shoes	1.22
7. Tyvek Coverall Ensemble	T-shirt, Men's underwear briefs, Socks, Athletic shoes, Tyvek coverall (no hood)	1.21
8. Fire Fighter Turnout Gear	Fire fighter helmet, T-shirt, Fire fighter turnout jacket, Green leather gloves, Men's underwear briefs, Fire fighter turnout pants, Socks, Work boots	1.48
9. Chemical Protective Level A Ensemble	Level A one-piece suit, Respirator, Men's underwear briefs, Socks, Athletic shoes	1.65

[2]: *ASTM F 1291-10 Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin*. 2010.

Appendix F: Statistical Analysis Results

Predicted Heat Loss Potential (Q value) - Standing with still air

Anova: Single Factor				
SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Control	3	595.3	198.433333	14.86333333
Vented	3	655.8	218.6	63.79
Polo/Knit	3	645.3	215.1	17.59

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	696.722222	2	348.361111	10.85876078	0.01014356	5.14325285
Within Groups	192.486667	6	32.0811111			
Total	889.208889	8				

t-Test: Two-Sample Assuming Equal Variances

	Control	*Vented*
Mean	198.433333	218.6
Variance	14.8633333	63.79
Observations	3	3
Pooled Variance	39.3266667	
Hypothesized Mean Difference	0	
df	4	
t Stat	-3.9385483	
P(T<=t) one-tail	0.00849025	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.01698049	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances

	Vented	*Polo/Knit*
Mean	218.6	215.1
Variance	63.79	17.59
Observations	3	3
Pooled Variance	40.69	
Hypothesized Mean Difference	0	
df	4	
t Stat	0.67200086	
P(T<=t) one-tail	0.26920083	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.53840166	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances

	Control	*Polo/Knit*
Mean	198.433333	215.1
Variance	14.8633333	17.59
Observations	3	3
Pooled Variance	16.2266667	
Hypothesized Mean Difference	0	
df	4	
t Stat	-5.0673362	
P(T<=t) one-tail	0.00357186	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.00714373	
t Critical two-tail	2.77644511	

Predicted Heat Loss Potential (Q value) - Walking with wind

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Control	3	1040.5	346.833333	3.253333333		
Vented	3	1155.7	385.233333	13.12333333		
Polo/Knit	3	1028.1	342.7	13.39		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3300.72889	2	1650.36444	166.3301232	5.5611E-06	5.14325285
Within Groups	59.5333333	6	9.92222222			
Total	3360.26222	8				

t-Test: Two-Sample Assuming Equal Variances		
	Control	*Vented*
Mean	346.833333	385.2333333
Variance	3.25333333	13.12333333
Observations	3	3
Pooled Variance	8.18833333	
Hypothesized Mean Difference	0	
df	4	
t Stat	-16.435355	
P(T<=t) one-tail	4.012E-05	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	8.024E-05	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances		
	Vented	*Polo/Knit*
Mean	385.233333	342.7
Variance	13.1233333	13.39
Observations	3	3
Pooled Variance	13.2566667	
Hypothesized Mean Difference	0	
df	4	
t Stat	14.3073065	
P(T<=t) one-tail	6.9323E-05	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.00013865	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances		
	Control	*Polo/Knit*
Mean	346.833333	342.7
Variance	3.25333333	13.39
Observations	3	3
Pooled Variance	8.32166667	
Hypothesized Mean Difference	0	
df	4	
t Stat	1.75485365	
P(T<=t) one-tail	0.07707003	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.15414006	
t Critical two-tail	2.77644511	

Total Thermal Resistance (R_t) - Standing with still air

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Control	3	0.5482	0.18273333	4.81333E-06		
Vented	3	0.5128	0.17093333	3.84333E-06		
Polo/Knit	3	0.5069	0.16896667	5.14333E-06		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00033263	2	0.00016631	36.15531401	0.00044977	5.14325285
Within Groups	0.0000276	6	4.6E-06			
Total	0.00036023	8				

t-Test: Two-Sample Assuming Equal Variances		
	Control	*Vented*
Mean	0.18273333	0.170933333
Variance	4.8133E-06	3.84333E-06
Observations	3	3
Pooled Variance	4.3283E-06	
Hypothesized Mean Difference	0	
df	4	
t Stat	6.94651995	
P(T<=t) one-tail	0.00112801	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.00225602	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances		
	Vented	*Polo/Knit*
Mean	0.17093333	0.168966667
Variance	3.8433E-06	5.14333E-06
Observations	3	3
Pooled Variance	4.4933E-06	
Hypothesized Mean Difference	0	
df	4	
t Stat	1.13629754	
P(T<=t) one-tail	0.15964543	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.31929085	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances		
	Control	*Polo/Knit*
Mean	0.18273333	0.168966667
Variance	4.8133E-06	5.14333E-06
Observations	3	3
Pooled Variance	4.9783E-06	
Hypothesized Mean Difference	0	
df	4	
t Stat	7.55670451	
P(T<=t) one-tail	0.00082171	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.00164341	
t Critical two-tail	2.77644511	

Total Thermal Resistance (R_t) – Walking with wind

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Control	3	0.3571	0.11903333	4.09333E-06		
Vented	3	0.339	0.113	1.2E-07		
Polo/Knit	3	0.3438	0.1146	0.00001597		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.8616E-05	2	2.9308E-05	4.356234517	0.06782613	5.14325285
Within Groups	4.0367E-05	6	6.7278E-06			
Total	9.8982E-05	8				

t-Test: Two-Sample Assuming Equal Variances		
	Control	*Vented*
Mean	0.11903333	0.113
Variance	4.0933E-06	1.2E-07
Observations	3	3
Pooled Variance	2.1067E-06	
Hypothesized Mean Difference	0	
df	4	
t Stat	5.09102275	
P(T<=t) one-tail	0.00351322	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.00702644	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances		
	Vented	*Polo/Knit*
Mean	0.113	0.1146
Variance	1.2E-07	0.00001597
Observations	3	3
Pooled Variance	8.045E-06	
Hypothesized Mean Difference	0	
df	4	
t Stat	-0.6908799	
P(T<=t) one-tail	0.26382108	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.52764217	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances		
	Control	*Polo/Knit*
Mean	0.11903333	0.1146
Variance	4.0933E-06	0.00001597
Observations	3	3
Pooled Variance	1.0032E-05	
Hypothesized Mean Difference	0	
df	4	
t Stat	1.71431044	
P(T<=t) one-tail	0.08081145	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.16162291	
t Critical two-tail	2.77644511	

Total Evaporative Resistance (R_{et}) – Standing with still air

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Control	3	0.07448	0.02482667	4.35033E-07		
Vented	3	0.06694	0.02231333	1.28813E-06		
Polo/Knit	3	0.06865	0.02288333	3.77733E-07		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.0418E-05	2	5.2091E-06	7.438447015	0.02373865	5.14325285
Within Groups	4.2018E-06	6	7.003E-07			
Total	1.462E-05	8				

t-Test: Two-Sample Assuming Equal Variances		
	Control	*Vented*
Mean	0.02482667	0.022313333
Variance	4.3503E-07	1.28813E-06
Observations	3	3
Pooled Variance	8.6158E-07	
Hypothesized Mean Difference	0	
df	4	
t Stat	3.31624857	
P(T<=t) one-tail	0.01474084	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.02948168	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances		
	Vented	*Polo/Knit*
Mean	0.02231333	0.022883333
Variance	1.2881E-06	3.77733E-07
Observations	3	3
Pooled Variance	8.3293E-07	
Hypothesized Mean Difference	0	
df	4	
t Stat	-0.7649189	
P(T<=t) one-tail	0.24347809	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.48695619	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances		
	Control	*Polo/Knit*
Mean	0.02482667	0.02288333
Variance	4.3503E-07	3.7773E-07
Observations	3	3
Pooled Variance	4.0638E-07	
Hypothesized Mean Difference	0	
df	4	
t Stat	3.73357591	
P(T<=t) one-tail	0.0101169	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.0202338	
t Critical two-tail	2.77644511	

Total Evaporative Resistance (R_{et}) – Walking with wind

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Control	3	0.04071	0.01357	9.1E-09		
Vented	3	0.03607	0.01202333	2.14333E-08		
Polo/Knit	3	0.04189	0.01396333	4.01333E-08		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.3105E-06	2	3.1552E-06	133.9490566	1.0512E-05	5.14325285
Within Groups	1.4133E-07	6	2.3556E-08			
Total	6.4518E-06	8				

t-Test: Two-Sample Assuming Equal Variances		
	Control	*Vented*
Mean	0.01357	0.01202333
Variance	9.1E-09	2.1433E-08
Observations	3	3
Pooled Variance	1.5267E-08	
Hypothesized Mean Difference	0	
df	4	
t Stat	15.3309915	
P(T<=t) one-tail	5.2798E-05	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.0001056	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances		
	Vented	*Polo/Knit*
Mean	0.01202333	0.013963333
Variance	2.1433E-08	4.01333E-08
Observations	3	3
Pooled Variance	3.0783E-08	
Hypothesized Mean Difference	0	
df	4	
t Stat	-13.54221	
P(T<=t) one-tail	8.6048E-05	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.0001721	
t Critical two-tail	2.77644511	

t-Test: Two-Sample Assuming Equal Variances		
	Control	*Polo/Knit*
Mean	0.01357	0.013963333
Variance	9.1E-09	4.01333E-08
Observations	3	3
Pooled Variance	2.4617E-08	
Hypothesized Mean Difference	0	
df	4	
t Stat	-3.0703774	
P(T<=t) one-tail	0.01863963	
t Critical one-tail	2.13184679	
P(T<=t) two-tail	0.03727926	
t Critical two-tail	2.77644511	