Design Implementation, Fabric Analysis, and Physiological and Subjective Testing of a Sportswear Garment Prototype

by

Khalil Andrew David Henry Michael Robert Lee

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Approved by

David Pascoe, Chair, Assistant Director, School of Kinesiology
Helen Koo, Assistant Professor, Department of Design, University of California Davis
Mary Rudisill, Director, School of Kinesiology
Matt Miller, Assistant Professor, School of Kinesiology

ABSTRACT

The present study focused on the objective and subjective evaluation of a sportswear shirt prototype designed for hot environments in its ability to regulate heat transfers, moisture transport, and provide overall wearer comfort.

In the first part of the study, the thermophysiological comfort properties (i.e. thermal conductivity, thermal resistance, air permeability, water vapor transport, and wicking ability) of fabric samples from the prototype (NEW-J and NEW-P) were tested using textile-based laboratory methods. The prototype fabric samples were compared to a polyester/spandex fabric sample (POLY) and a cotton sample (COT). The results suggested that the thermophysiological comfort properties of the fabrics appear to be affected by their knit structure more than their fiber properties alone.

In the second part of the study, wearer trials were performed to investigate the effects of the prototype on physiological and subjective responses while cycling in a hot, dry environment. The prototype (NEW) was compared to two commercially produced hot-weather sportswear shirts comprised of the fabrics from the first part of the study (COT and POLY). Twelve healthy, active males performed 3 randomized trials on an electronic cycle ergometer in a controlled environment (35°C, 40% RH, 2 m/s air velocity). The cycling protocol consisted of a 45-min. bout at 50% of each participant's VO_2max workload, followed by a 12-mile time trial. Heart rate (HR), core temperature (T_c), mean torso skin temperature ($T_{sktorso}$), and perceived exertion (RPE) were recorded every 5 minutes throughout the 45-min. bout. Ratings of thermal sensation, thermal comfort, and wetness sensation were recorded during the 45-min. bout at minutes 0, 15, 30, and 45, and immediately following the completion of the 12-mile time trial. Ratings of thermal sensation for NEW were significantly better than both COT and POLY at 15 min. ($p < .05$), 30 min. ($p < .05$), and post time trial ($p < .001$ and $p < .01$, respectively). Thermal comfort in NEW was significantly better than COT at 15 min. ($p < .05$), 30 min. ($p < .05$), post 45 min. ($p < .01$), and post time trial ($p < .01$). Wetness sensation in NEW was significantly better than both COT and POLY at post 45 min. ($p < .001$ and $p < .05$, respectively) and post time trial ($p < .01$ and $p < .05$, respectively). No significant differences between shirts were observed for HR, T_c ($p = .07$), $T_{sktorso}$, sweat loss, or 12-mile trial completion time ($p = .11$). Results revealed more favorable comfort responses for the prototype shirt. Although the prototype did not produce statistically significant thermophysiological effects, it’s important to note that apparel marketers may acknowledge statistical values less stringent than $p \leq .05$.

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LIST OF ABBREVIATIONS

S	Heat storage
M	Metabolic heat
C_v	Convective heat
C_d	Conductive heat
R	Radiant heat
E	Evaporative heat
λ	Thermal conductivity
R	Thermal resistance
h	Fabric thickness
WVTR	Water vapor transmission rate
VO_2max	Maximum volume of oxygen consumption
W	Watts
rpm	Revolutions per minute
RH	Relative humidity
HR	Heart rate
T_c	Core temperature
$T_{sktorso}$	Torso skin temperature
T_{chest}	Skin temperature of the chest
T_{back}	Skin temperature of the back
RPE	Rating of perceived exertion

I. INTRODUCTION

Clothing creates a barrier to heat transfer between the human body and the external environment [1]. In the past, clothing was worn simply for insulation and aesthetic purposes [2], and the textile materials used were not as plenteous as they are today. In fact, the role of clothing in hot environments received little scientific attention prior to the 1960's [3]. Clothing has now been engineered with greater functionality to maximize comfort and facilitate the maintenance of thermal homeostasis in the midst of various physical and environmental variables [4].

The core temperature set point of the human body is approximately 37 ± 0.2°C [5]. During physical activity, the body generates metabolic heat, which must be dissipated in order to maintain a stable core temperature. Clothing can impede evaporative heat loss, which is the primary means of heat loss during physical activity. The combination of clothing and physical activity in a hot environment produces more rapid increases in heat storage, and wearer comfort is also adversely affected [5, 6]. Increases in heat production and heat gain without efficient heat loss puts the body in danger of heat related illness and, in the worst case, death [7, 8].

As a result, many garments have been produced in the sports and exercise apparel industry to keep the wearer cooler, drier, and more comfortable in hot environments [9]. These activewear or sportswear garments, as they are commonly called, have been in high demand in the apparel market over the past few decades. Sales of these garments amassed billions of dollars in revenue in the year 2013 alone (Table 1).

Table 1. 2013 Sportswear Apparel Revenue Figures

Nike, Inc.	$3.03 billion [10]
Under Armour, Inc.	$1.76 billion [11]
Adidas AG	€5.813 billion* [12]

*Denotes worldwide revenue.

Different materials and technologies have been incorporated into these garments, including synthetic fabric blends, fabric channels, and ventilation panels. The manufacturers of these garments claim their products provide enhanced heat dissipation, moisture management, and overall thermal comfort. However, these claims have not been well supported by scientific evidence [13]. The recent designs of most sportswear garments impede heat dissipation and reduce comfort, which presents a negative effect on health and performance [14]. Therefore, new designs that more effectively alleviate heat stress and improve wearer comfort must be developed.

II. REVIEW OF LITERATURE

Interactions between Thermal Balance and Clothing

The human body is constantly exposed to transient internal and external environmental conditions. Despite these conditions, the body strives to maintain a tightly regulated core body temperature of 37 ± 0.2 °C [5]. Adjustments to skin blood flow, hormone levels, and the activation of sweat glands take place to preserve core temperature within a narrow range [13]. The process is thermoregulation is a balance between heat production and heat dissipation, and this balance can be represented by the heat exchange equation:

$S = M \pm C_v \pm C_d \pm R - E,$

where S is heat storage, M is metabolic heat production, C_v is convective heat loss or gain, C_d is conductive heat loss or gain, R is radiant heat loss or gain, and E is evaporative heat loss [15]. In order to thermoregulate, the body must dissipate the heat that is gained from metabolic activity and the ambient environment through radiation, conduction, convection, and evaporation [16]. The first three heat loss mechanisms require a temperature gradient to exist, while evaporation requires a vapor pressure gradient to exist between the skin and the external environment [17]. Radiation is the transfer of heat waves from the surface of one object to the surface of another, without those objects being in contact. Heat loss via radiation can occur in environments where the skin temperature is greater than the temperature of surrounding objects, as the radiant heat is transferred down the gradient from the warmer to the cooler heat source [17]. Conduction is the transfer of heat from the surface of the body to the surface of another object through direct contact. Heat exchange through convection occurs as air or water molecules come in contact with the body. In evaporation, heat is transferred as water molecules in human sweat change from a liquid to a gas state [17]. When thermal balance is attained, the amount of heat storage equals 0 [16].

Exercise in the Heat

Human thermoregulation is often challenged by a variety of factors, including ambient temperature and humidity, physical activity, and clothing. In hot outdoor environments, where ambient temperatures are greater than the skin temperature, the body can gain heat through radiation from the sun [1, 8, 9, 17]. Increased cellular work from exercise causes an increase in metabolic heat production, thereby increasing heat storage. As a result, blood flow to the skin increases and the nervous system stimulates the secretion of sweat in order to dissipate the heat [18]. During exercise, the evaporation of sweat can account for as much as 80% of the heat loss from the body [13]. However, the rate of evaporative heat loss is reduced in hot, humid environments due to a reduction in the vapor pressure gradient between the skin and the ambient environment [17].

It has been well documented that exercise in the heat can have detrimental consequences, including heat-related illness and even death [7, 8]. An estimated 9,000 plus high school athletes are treated for exertional heat illness each year [19]. Core temperatures in excess of 40°C make the body susceptible to exertional heat stroke [7, 20]. Exercise in the heat can even impair cognitive function [21] and hinder exercise performance [22].

Impacts of Clothing

Clothing creates a barrier to heat transfer between the skin and the external environment [1], impeding the dissipation of heat and moisture to the external environment [1, 9, 23]. As stated earlier, the evaporation of sweat from the skin is the prominent means of heat loss during exercise. Sweating increases the humidity in the clothing microclimate, or the space between the inside layer of clothing and the skin [24]. The evaporation of sweat from the skin is dependent upon the air velocity as well as the vapor pressure gradients between the skin, the clothing, and the ambient air [25]. Clothing can interfere with convective and evaporative heat loss [13], causing increases in skin and core temperature, as well as a reduction in cooling efficiency are the result [5, 26]. The buildup of moisture in the microclimate also causes sensations of wetness and clamminess, which reduce wearer comfort [24]. In fact, moisture in clothing causing skin wetness is one of the most important factors adversely affecting thermal comfort [4, 9, 27]. If clothing impedes heat dissipation, then the combination of clothing and exercise in the heat puts the human body at an even greater risk of heat illness.

Therefore, it's vital to understand the materials used in functional clothing ensembles and how they impact thermoregulation and comfort. The effects of clothing on thermoregulation and comfort, first of all, depend on the textile materials used and the properties of those materials [28]. In the next section, previous literature examining the heat and moisture management properties of clothing fabrics will be reviewed.

Properties of Fabrics and Clothing Materials

Textile Materials

Textile materials are the basic unit of most fabrics, and they contribute to a garment's performance [29]. There four components of textile materials include fibers, yarns, fabrics (i.e. the type of weave or knit structure), and finishes. Fibers are the smallest components of fabrics. They have a high length-to-width ratio and can be natural or synthetic. Yarns are strands of fibers formed by twisting or laying together the fibers. Fabrics refer to the planar construction of fibers and yarns. Fabric finishes are the various substances or processes which add color or improve the performance of the fabric in some way [29]. Therefore, one must consider the type of materials used when developing clothing ensembles.

Textile Fibers and their Properties

Cotton, a natural fiber, has a soft hand (i.e. the way a fiber feels) and is ideal for use in dry conditions [29]. However, it readily absorbs and retains sweat, which hinders the transfer of moisture [23] and causes a wet, clammy sensation and fabric heaviness [9, 16, 29]. Synthetic fibers, such as polyester and nylon, are hydrophobic, meaning they absorb less moisture than natural fibers [29]. These fibers are often a main component in warm-weather sportswear garments, as they are purported to improve moisture wicking and water vapor permeation to keep the wearer drier [9, 30].

Studies Examining Thermal Comfort Properties of Fabrics

Clothing comfort is comprised primarily of the following three aspects: psychological, sensorial, and thermophysiogical comfort [4, 31]. Thermophysiological comfort involves the transport of both heat and moisture through fabric [4]. Properties of thermophysiological comfort include thermal conductivity, thermal resistance, air permeability, water vapor transport, wicking ability, and drying rate [32-35]. It is known that these properties are influenced by the materials of textiles, which include the fiber content, yarn properties, fabric structure, and finishing treatments [31, 32]. Thermal conductivity (λ) refers to a material's ability to allow heat transfer via conduction, whereas thermal resistance (R) refers to its ability to inhibit heat from flowing through it [31]. Both are measured in regards to the transfer of dry heat through areas of clothing in contact with the skin. Air permeability refers to the exchange of air flow through fabric [36]. Water vapor transport examines a fabric's ability to allow water vapor to transfer through it to the external environment, which is determined by the vapor pressure gradients between the microclimate and the external environment [24]. Wicking is the ability of a fabric to move liquid moisture along its capillaries once the fibers have become wet [29, 33].

Extensive research has been conducted on the thermal comfort properties of woven [32, 37, 38] and knitted fabrics [24, 31, 34, 35, 39-47] using textile-based laboratory methods, including thermal manikins [2, 48-53]. Yoo and Barker [37] examined the liquid moisture transfer properties in a group of woven workwear fabrics using a demand wettability test. They inferred that a garment made of cotton fabric may cause a clammy feeling despite its superior absorbent capacity and rate of absorption. Research by Hes and Loghin [32] showed measures of thermal conductivity dramatically increased, while measures of thermal resistance and air permeability decreased as the moisture content increased in cotton and polyester woven fabrics. Saricam and Kalaoglu [38] investigated the effects of yarn type, weft density, weave structure, fabric thickness, and air permeability on the wicking and drying behavior of polyester woven fabrics. Changing the weft density and weave type was found to influence wicking performance. Moreover, the drying rate was inversely related to fabric thickness.

Knitted fabrics are the most commonly used for functional sportswear garments due to their good handle and ability to provide greater freedom of movement [31]. The types of fibers used play an important role in the heat and moisture management capabilities of knitted fabrics. For example, synthetic fibers (e.g. polyester) are often used preferably over natural fibers in sportswear fabrics because of their lower capacity for absorbing moisture and ability to transport water vapor [13]. However, several fabric studies have shown that the yarn and structural aspects of the fabric, which determine variables such as fabric thickness and porosity, can play a greater role in the thermophysiological comfort properties than fiber type alone [24, 31]. Prahsarn et al. [24] measured the moisture vapor transport behavior of polyester knit fabrics using different test methods. They found moisture vapor transmission rate to be highly dependent upon the thickness of the fabric, as thicker fabrics provide a greater distance through which moisture vapor must pass. Moreover, knitted fabrics with higher air permeability produced shorter microclimate drying times than those with lower air permeability. Oglakcioglu and Marmarali [31] found similar trends in both cotton and polyester knit fabrics on thermal comfort properties. Measures of thermal conductivity and thermal resistance increased with fabric thickness, while water vapor permeability was lower for thicker fabrics. A positive relationship between fabric thickness and thermal resistance was also seen in a study by Cubric et al. [46]. Bedek et al. [45] evaluated heat and moisture transfer properties in a group of commercially produced underwear fabrics designed for sportswear applications. The authors found that fabrics with higher moisture regains were correlated with higher values of thermal conductivity, lower values of thermal resistance, and longer drying times. Additionally, fabrics with greater air permeability had shorter drying times, which is a similar finding to that of Prahsarn et al. [24].

Fangueiro et al. [44] analyzed the wicking and drying capabilities of different functional knitted fabrics. Their results revealed a better drying rate for fabrics having a lower moisture regain and a better wicking ability. Similarly, Laing et al. [34] reported positive correlations between drying time and the mass of water retained in a fabric after wetting and also between drying time and fabric thickness. The findings from the studies by Fangueiro et al. [44] and Laing et al. [34] were confirmed by Yanilmaz and Kalaoglu [47], who found an inverse relationship between drying rate and fabric thickness when testing acrylic knitted fabrics. Thickness increased the compactness of the fabric, which decreased the air space necessary for the evaporation of moisture. The authors added that wicking ability was largely dependent upon fabric contact angles. Slack fabrics, having larger pore sizes and lower contact angles, wicked moisture at a higher rate than tight fabrics, which have higher contact angles.

Many of the test procedures in the studies previously mentioned were steady-state procedures, which are beneficial in providing reproducible results [33]. However, the human body is constantly exposed to transients during physical activity and different environmental conditions [4]. Therefore, fabric performance should also be explored under transient states, using human experimental protocols, in order to determine the effectiveness of a garment for real-life conditions [33]. Studies using human methods, primarily those involving exercise protocols in hot environments, will be discussed in the next section.

Clothing Effects on Physiological and Subjective Responses

The manufacturing of functional garments targeted towards physically active individuals has increased dramatically over recent decades [13], and consequentially the body of literature investigating the impacts of these garments on thermophysiology and comfort has grown. Synthetic fiber blends, ventilation panels, and other fabric technologies are often incorporated in functional sportswear garments, with claims of alleviating thermal stress, effectively managing moisture, and enhancing wearer comfort [9, 30]. A few earlier studies [23, 54] showed that synthetic garments had a worse effect on measures of thermophysiology than natural fabrics. Ha et al. [54] compared the effects of wearing a polyester clothing ensemble versus cotton during brief bouts of exercise and rest at 24°C, 50% RH. Both core temperature and pulse rate were significantly higher for polyester than cotton. Kwon et al. [23] compared the effects of wearing either polyester, cotton, or a wool/cotton blend during intermittent exercise in a hot environment with and without wind. No significant differences between garments were found in core, skin, or body temperature without wind. However, a significantly higher skin temperature, body temperature, and pulse rate was found in polyester compared to the other garments when subjects were exposed to a wind velocity. The researchers in both of the previous studies used women as their subjects.

The majority of studies performed on these garments have shown no significant differences on thermophysiological variables [30, 55-66] and subjective comfort variables [23, 30, 57-59, 61, 62, 67] between synthetic and natural garments. Gavin et al. [30] examined the effects of wearing a polyester clothing ensemble versus cotton during a protocol involving 15 minutes of rest, 30 minutes of running at 70% VO_2max, 15 minutes of walking at 40% VO_2max, and 15 minutes of rest, all at 30°C, 35% RH. There were no differences between garments for any of the thermoregulatory or comfort responses measured. Similarly, Wickwire et al. [57] reported no differences between cotton and a commercial wicking shirt on rectal temperature, skin temperature, heart rate, and comfort. Subjects wore each shirt under a bulletproof vest while doing a 2-hour protocol comprised of walking and bicep curls in an environment set at 35°C.

Brazaitis et al. [59] had subjects perform three 20-minute bouts of running at 8 km/h, followed by a 60-minute recovery period in an environment in a warm and humid environment. Thermophysiological and subjective responses were similar between polyester and cotton shirts during exercise. However, ratings of thermal sensation and shivering/sweating sensation were significantly better in the polyester shirt at the end of the recovery period. Stapleton et al. [62] compared the effects of wearing a synthetic fabric (93% polyester, 7% spandex) versus a cotton fabric under mining coveralls. Subjects performed 60 minutes of cycling at a constant rate of 400 W followed by 60 minutes of recovery at 40°C, 15% RH. The authors found no differences in skin temperature, core temperature, heart rate, or thermal sensation between fabrics when worn under the coveralls.

A limited number of studies have shown significantly better measures of thermophysiology [67] and comfort [55, 56, 63] when wearing synthetic sportswear garments, while a few studies [61, 65, 68] have shown significant differences between sportswear garments with different fabric knit structures. Gonzales et al. [68] found lower torso skin temperature, jersey temperature, and perceived hotness in polyester jerseys with large knits (3.5 mm) compared to small knits during exercise performed in a hot environment.

Considerations for Garment Design

Current designs of sportswear garments often employ blends of synthetic fabrics (e.g. polyester and spandex), fabric channels [65], ventilation features [2], and chemical finishes. Functional sportswear garments should be designed to match the garment's attributes with thermoregulatory function and perceptual comfort. Finding ways to minimize resistance to evaporative and convective heat loss are targets of consideration when designing these garments.

Purpose and Rationale

Only a limited number of studies [35, 41, 42, 50] have followed textile-based laboratory tests with subsequent wearer trials to thoroughly examine the thermophysiological comfort properties of functional garments. This study will incorporate aspects of textile design, textile engineering, and exercise physiology to assess the performance of a sportswear garment prototype designed for hot environments. First, the thermophysiological comfort properties of the garment fabric will be evaluated using textile-based laboratory methods. Next, the effects of the garment on measures of thermophysiology and subjective comfort during exercise in a hot, dry environment will be investigated using human subjects.

The information gained in this study will be beneficial to the manufacturer of the garment prototype to determine if further modifications or improvements to the garment are necessary prior to its mass production. It will also add to the body of research on sportswear garments and their effects on human thermoregulation and comfort.

III. JOURNAL MANUSCRIPT 1

Introduction

Clothing has evolved from a product simply meeting our basic needs of protection to a device functionally designed to help us face different environmental conditions [2, 4]. Sportswear garments have been heavily marketed in the apparel industry over the past decade [13], many of which are designed with the intention of keeping the active individual cooler, dryer, and more comfortable in hot environments [9, 30, 69]. These garments incorporate various materials and technologies to enhance their ability to effectively manage heat and moisture produced from the body, such as synthetic fiber blends [4], fabric channels, and chemical finishes [70].

Physical activity increases metabolic heat production. Therefore, the regulation of a stable core temperature depends on our ability to dissipate metabolic heat (as well as the heat gained from the environment) via conduction, convection, radiation, and evaporation [16]. Physical activity in combination with hot environmental conditions can cause significant rises in core temperature, leading to diminished performance [22] and higher risk of heat-related illness [8, 20, 22]. Clothing impairs the dissipation of heat and moisture, thereby complicating thermoregulation and promoting wearer discomfort [5, 18, 26].

With this in mind, sportswear garments designed for hot environments must be able to effectively alleviate thermal stress and promote thermophysiological comfort. Thermophysiological comfort is dependent upon the transport of heat and moisture through fabric, and it is one of the most desired attributes of sportswear products [4]. Thermal conductivity, thermal resistance, air permeability, water vapor transport, and wicking ability are important properties affecting the thermal behavior and comfort level of garments [32, 33].

Thermal conductivity (λ) refers to a material's ability to allow heat transfer via conduction, whereas thermal resistance (*R*) refers to its ability to inhibit heat from flowing through it [31]. Dry heat may be conducted from the skin to the garment in areas where the garment is in contact with the skin. Air permeability refers to the exchange of air flow through fabric [36]. Previous studies have shown that an increase in air exchange through the fabric of a garment increases dry and evaporative heat loss [48, 71]. Water vapor transport examines a fabric's ability to allow water vapor to transfer through it to the external environment, which is determined by the vapor pressure gradients between the microclimate and the external environment [24]. Wicking is the ability of a fabric to move liquid moisture along its capillaries once the fibers have become wet [29, 33]. Moisture buildup in clothing is one of the most important factors adversely affecting wearer comfort [4, 9, 27]. The human body secretes sweat for evaporative cooling. As sweating proceeds, humidity increases in the clothing's microclimate, or the air space between the inside layer of clothing and the skin [24]. The accumulation of sweat saturates the microclimate, causing feelings of wetness and clamminess that are often discomforting to the wearer [4, 24]. Therefore, the transport of evaporative perspiration and liquid perspiration (via wicking) play important roles in maintaining thermophysiological comfort [33].

Numerous studies have investigated the thermal comfort properties of functional knitted fabrics. For instance, Prahsarn et al. [24] assessed the moisture vapor transport behavior of polyester fabrics with different knit structures, yarn types, and fiber cross-sectional shapes. They found that moisture transmission was mostly controlled by fiber, yarn, and fabric variables that determine fabric thickness and porosity. Oglakcioglu and Marmarali [31] analyzed the effects of fabric structure on thermal properties, including thermal conductivity, thermal resistance, and water vapor permeability. Their results indicated that differing knit structures tend to produce differing thermal comfort properties. Fangueiro et al. [44] found that the wicking behavior of fabrics is primarily determined by the capillary pore distribution and pathways as well as surface tension. Similarly, Yanilmaz and Kalaoglu [47] reported slack fabrics having higher pore sizes produced higher wicking rates than tight fabrics. Overall, several studies have confirmed that the thermal comfort properties of functional sportswear fabrics are largely influenced by factors such as the fiber content, the structure of the knit, and the fabric thickness [31, 32].

The purpose of this study was to evaluate the thermal comfort properties (i.e. thermal conductivity, thermal resistance, air permeability, water vapor transport, and wicking ability) between four fabric samples from commercial sportswear garments designed for hot environments. Two of the samples were derived from a newly constructed garment prototype. The information gained from this study will be beneficial to the manufacturer of the garment prototype to determine if further modifications or improvements to the garment's thermal comfort properties are necessary prior to its mass production.

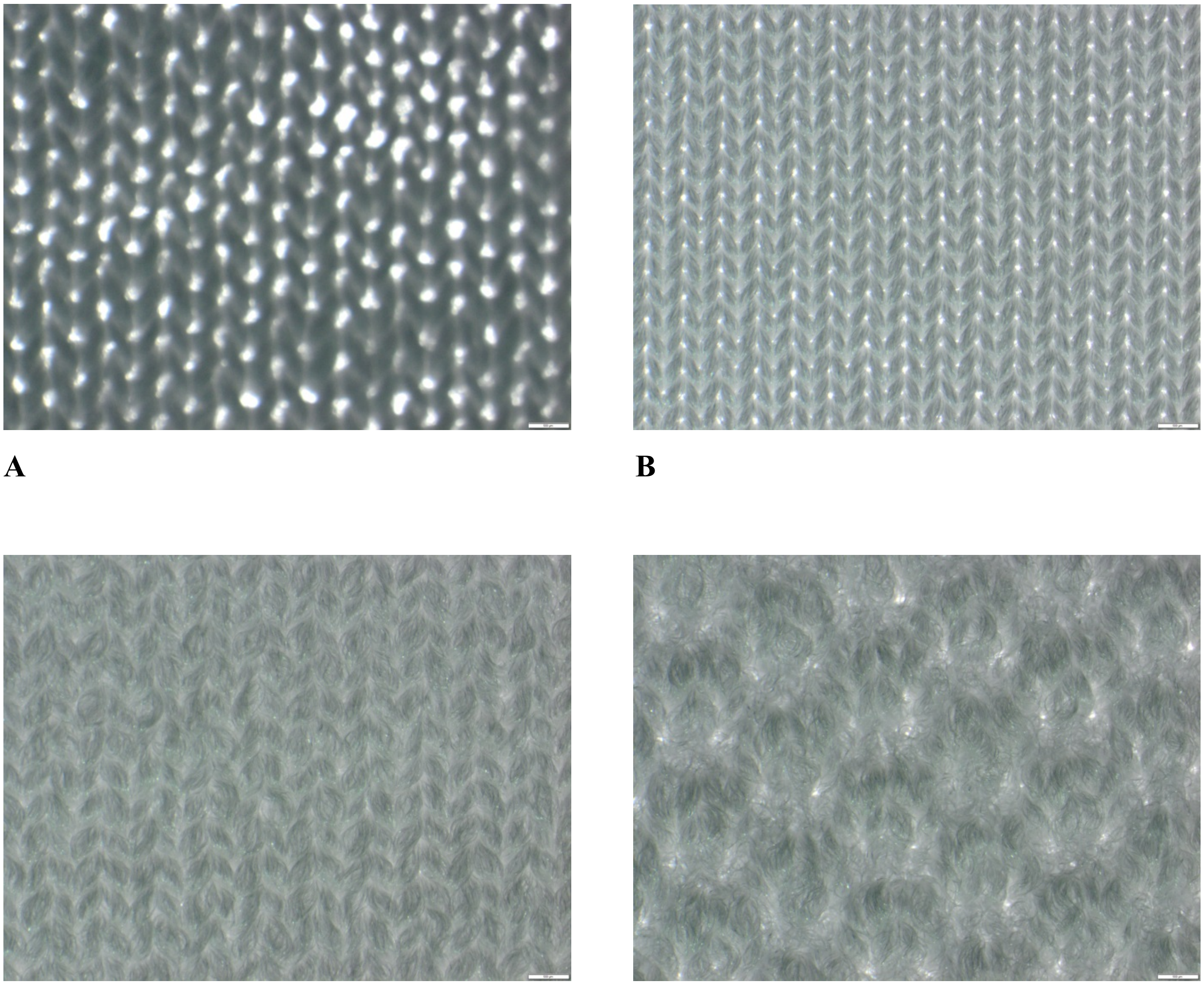
Methods

Materials

Four fabric samples from commercially produced sportswear garments were tested in a controlled laboratory environment. The samples differed in their fiber composition, fabric thickness and knit structure. The samples NEW-J and NEW-P were derived from the prototype for a new garment. The other two samples included a 100% cotton sample (COT) and an 84/16 polyester/spandex blended sample (POLY). Cotton products are still used widely in the sportswear market [72], while synthetic garments such as POLY are claimed to have superior wicking and moisture management properties [57]. The contents of the fabric samples are displayed in Table 1, and the microscopic views of each sample are displayed in Figure 1. A "course" denotes a row of loops along the width of a fabric, and a "wale" denotes a column of loops along the length of the fabric [42]. Prior to each test, all samples were cut and conditioned in the controlled environment for at least 24 hours.

Table 1. Fabric Specifications

Sample ***Including brand name***	**Fiber content**	**Knit structure**	**Thickness (mm)**	**Courses (#/cm)**	**Wales (#/cm)**
COT *Fruit of the Loom®*	100% cotton	Single jersey	0.58	20	14
POLY *BCG™*	84% polyester 16% spandex	Single jersey	0.5	32	21
NEW-J *Russell Athletic™*	90% nylon 10% spandex	Single jersey	0.91	24	15
NEW-P *Russell Athletic™*	90% nylon 10% spandex	Pique	1.11	8	5



A B

C D

Figure 1. Microscopic View of Fabric Samples: COT (A), POLY (B), NEW-J (C), and NEW-P (D).

Methods

Thermal conductivity and thermal resistance were measured using an Alambeta instrument, which enables rapid measurement of the steady-state thermal properties of fabrics [73]. The Alambeta simulates dry human skin, and its value is dependent on the amount of time in which heat passes from a measuring head through a tested fabric [32]. The thermal properties are attained as the fabric is pressed between the measuring head (32°C) and a bottom measuring plate (22°C) for less than one minute. Eight samples of each fabric were tested to ensure repeatability of results.

Measures of air permeability were examined using a Frazier Low Differential Pressure Air Permeability Tester (ASTM D737) [74]. This instrument was developed by the National Institute of Standards and Technology for measuring the air permeability of textile type materials and is the acknowledged standard for the U.S. Government and the U.S. Textile Industry. It determines the rate of airflow ($ft^3/min/ft^2$) as air passes through the fabric from an area of higher air pressure to an area with lower air pressure. Eight samples of each fabric were also tested for this measure.

Moisture vapor transmission was tested using the upright cup method (ASTM E96) [75]. For this method, three samples of each fabric were cut and sealed over an evaporating dish containing approximately 350 g of water. The initial weights of the dishes were recorded and then placed in an environmentally controlled cabinet (set at 23°C, 50% RH) for 24 hours. Following the 24-hour period, the dishes were removed from the cabinet and weighed once again. The pre-to-post weight differences were used to calculate water vapor transmission rate (WVTR) in $g/m^2/24$ hours. In this test, the ability of water to diffuse through the fabric is driven by the vapor pressure gradient between the more humid air within the cup and the less humid atmosphere in the environmental cabinet [24].

Wicking ability was analyzed using the vertical wicking test method (AATCC TM 197) [76]. Each fabric sample was cut into 250 mm x 25 mm (walewise x coursewise) strips and suspended vertically with the bottom end in a reservoir of 0.25% NaCl solution in order to simulate the properties of human sweat. This was the same solution used in a study by Simile [40], in which he analyzed the wicking performance of fabrics using different wicking test methods. A 1 g clip was clamped on the bottom end of each fabric sample to ensure the bottom ends of the samples stayed submerged in the solution [44]. The wicking heights were recorded every minute for the first 10 minutes and then every 10 minutes thereafter until an hour to observe both acute and prolonged wicking performance.

Statistical Analysis

All data are presented as mean ± SD. Data from all test measures, with the exception of wicking ability, were analyzed using a one-way ANOVA. Differences were considered statistically significant at $p \leq .05$. However, all P values have been presented for the sake of apparel marketers and manufacturers who may recognize the importance of less stringent statistical values. When statistical significance was found, Tukey post hoc analyses were run to determine differences between fabric samples. All statistical tests were carried out using SPSS Statistics Version 22 (IBM Corp.; Armonk, NY).

Results

Descriptive statistics of the thermal properties tested for each fabric sample are presented in Table 2.

Table 2. Thermal Properties of Fabrics

	Sample			
Variable	COT	POLY	NEW-J	NEW-P
Thermal conductivity (W/(m·K))*	0.042 ± 0.001	0.045 ± 0.001	0.057 ± 0.001	0.048 ± 0.001
Thermal resistance ((K·m^2)/W)*	0.013 ± 0.000	0.011 ± 0.000	0.016 ± 0.000	0.023 ± 0.000
Air permeability (ft^3/min/ft^2)*	216.2 ± 16.8	91.9 ± 4.3	42.2 ± 1.8	103.9 ± 3.9
WVTR (g/m^2/24h)	569.8 ± 7.5	586.5 ± 27.6	572.0 ± 15.9	613.3 ± 29.4
Vertical wicking ht. @ 10 min. (cm)	0.0	11.9	2.8	2.3
Vertical wicking ht. @ 60 min. (cm)	0.1	19.4	3.9	2.9

Values are reported as means ± SD (with the exception of vertical wicking ht.).
* Denotes significant difference between fabrics ($p < .001$).

Thermal Conductivity and Thermal Resistance

Figures 2 and 3 show the mean measures of thermal conductivity and thermal resistance, respectively, for the four fabric samples. Results from the one-way ANOVA revealed statistically significant differences between fabric samples for thermal conductivity ($p < .001$) and thermal resistance ($p < .001$). NEW-J conducted significantly more heat ($p < .001$) than COT, POLY, and NEW-P. Thermal conductivity for NEW-P was significantly higher ($p < .001$) than COT and POLY, while POLY was significantly higher ($p < .001$) than COT.

Measures of thermal resistance were the highest significantly ($p < .001$) for NEW-P compared to COT, POLY, and NEW-J. Thermal resistance for NEW-J was significantly higher ($p < .001$) than COT and POLY, and COT was significantly higher ($p < .001$) than POLY.

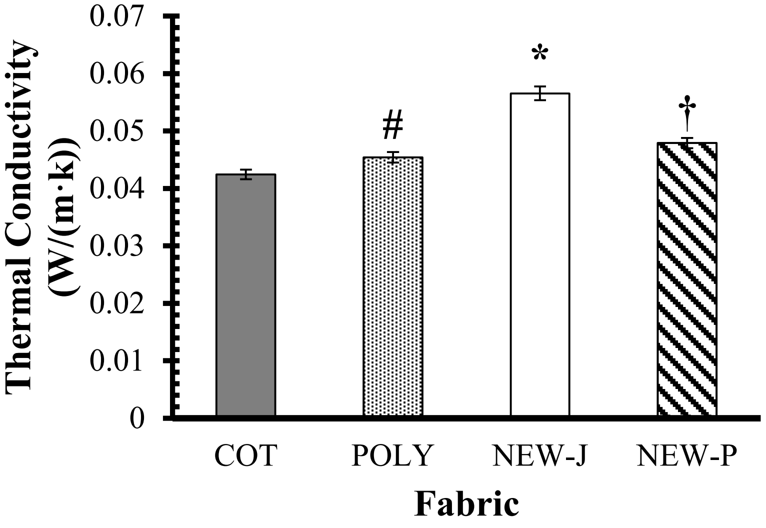


Figure 2. Thermal Conductivity between Fabric Samples. Values are reported as means ± SD. * NEW-J significantly higher than NEW-P, POLY, and COT ($p < .001$). † NEW-P significantly higher than POLY and COT ($p < .001$). # POLY significantly higher than COT ($p < .001$).

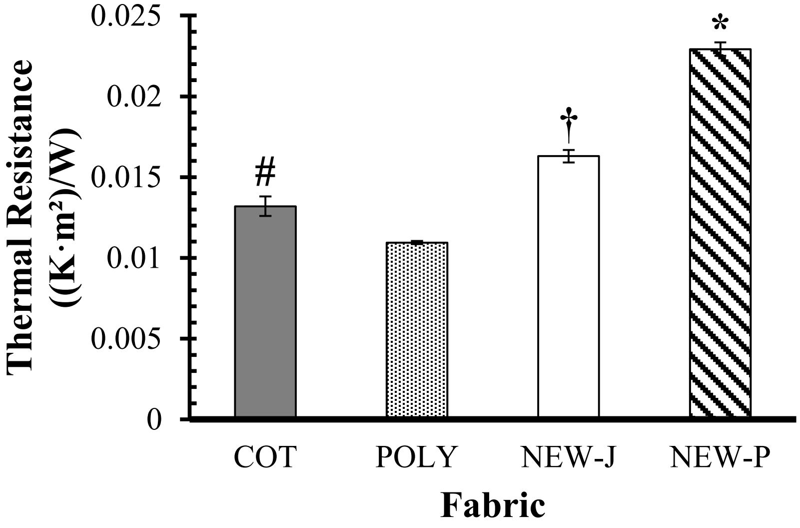


Figure 3. Thermal Resistance between Fabric Samples. Values are reported as means ± SD. * NEW-P significantly higher than NEW-J, POLY, and COT ($p < .001$). † NEW-J significantly higher than POLY and COT ($p < .001$). # COT significantly higher than POLY ($p < .001$).

Air Permeability

Comparisons of mean air permeability values between fabric samples are shown in Figure 4. Differences between samples were statistically significant ($p < .001$), with COT having the highest value (*p* < .001) compared to POLY, NEW-J, and NEW-P. POLY and NEW-P were both significantly higher (*p* < .001) than NEW-J, but were not significantly different from each other (*p* = .055).

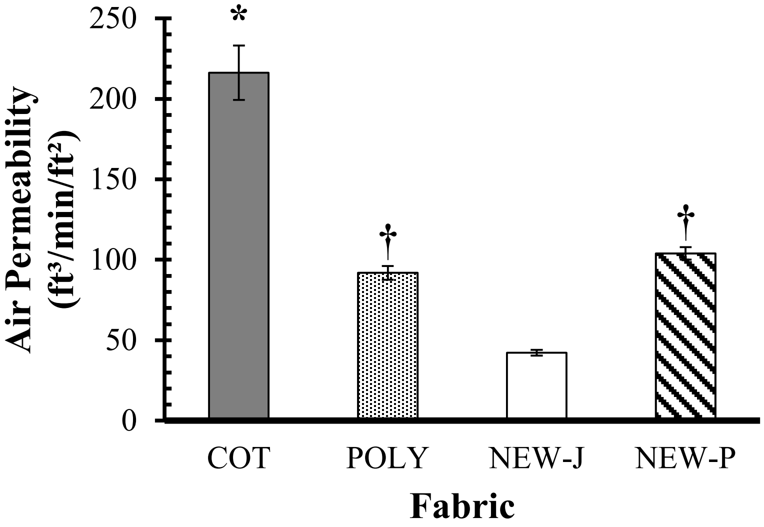


Figure 4. Air Permeability between Fabric Samples. Values are reported as means ± SD. * COT significantly higher than NEW-P, NEW-J, and POLY, (*p* < .001). † NEW-P and POLY significantly higher than NEW-J (*p* < .001).

Water Vapor Transmission Rate

WVTR comparisons are displayed in Figure 5. Measures were similar between all four fabrics (*p* = .136).

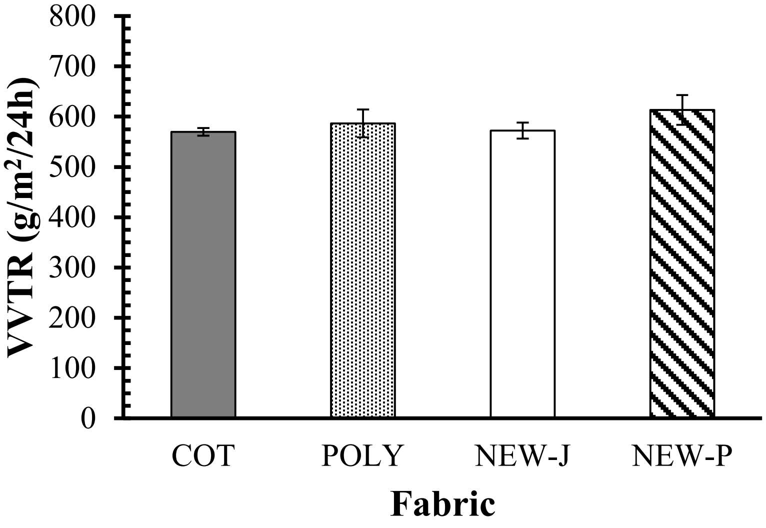


Figure 5. WVTR between Fabric Samples. Values are reported as means ± SD. No significant differences were found between fabrics.

Wicking Ability

Figures 6 and 7 show, respectively, the vertical wicking heights of the samples for an acute time period (10 minutes) and a prolonged time period (60 minutes). From both figures, it can be observed that the wicking heights for POLY were much higher than the other samples for both time periods (11.9 cm at 10 minutes and 19.4 cm at 60 minutes). The wicking heights for NEW-J and NEW-P were similar, as they rose no higher than 3 cm over the first ten minutes and then rose very slowly thereafter. COT had the lowest wicking heights of all fabrics, with 0 cm at 10 minutes and only 0.1 cm at 60 minutes.

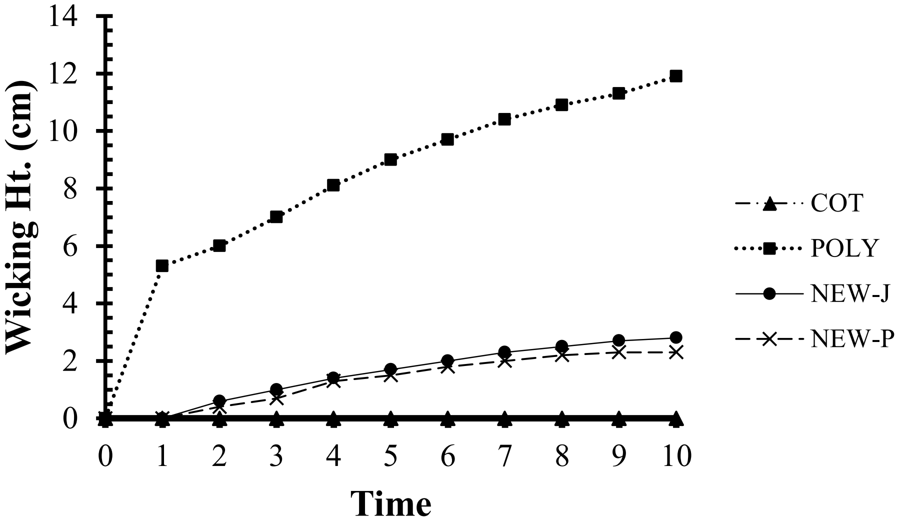


Figure 6. Vertical Wicking Height between Fabric Samples over 10 Minutes.

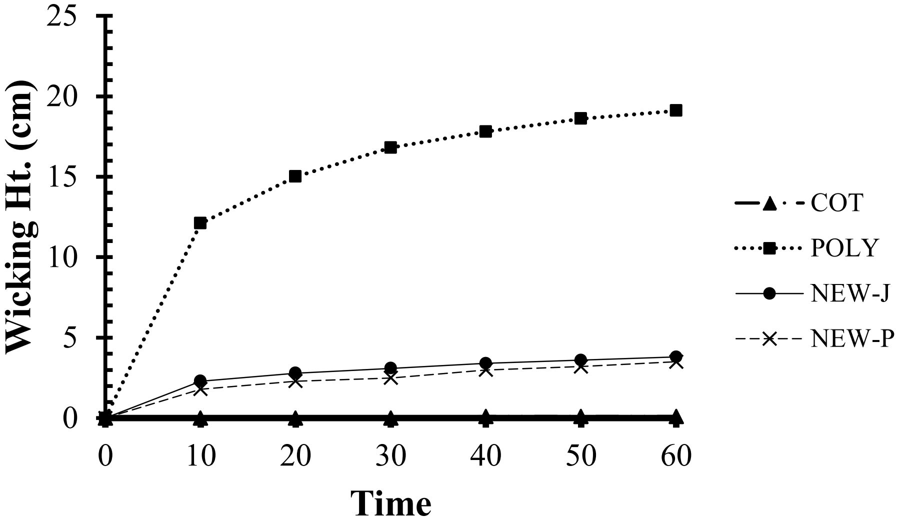


Figure 7. Vertical Wicking Height between Fabric Samples over One Hour.

Discussion

NEW-J had the significantly highest measure of thermal conductivity, followed by NEW-P. This may be explained by a smaller amount of entrapped air contained within both fabrics. As more air is entrapped within a fabric structure, thermal conductivity declines [31]. Although NEW-J and NEW-P yielded the highest measures of thermal conductivity, they also yielded the second highest and the highest measures of thermal resistance respectively. Normally, the relationship between thermal conductivity and thermal resistance is inverse, which is expressed by the following equation:

$R = h/\lambda$,

where R represents thermal resistance, h represents fabric thickness, and λ represents thermal conductivity [31]. If the fabric thickness is higher for a given thermal conductivity, thermal resistance will increase. In this study, NEW-J (h = 0.91 mm) and NEW-P (h = 1.11 mm) were the thickest fabrics, which was the reason for their higher measures of thermal resistance.

NEW-P was significantly more permeable to air then NEW-J, and it was also more permeable than POLY, although not significantly (p = .055). This may translate to enhanced thermal comfort in real-life wear conditions, as convective and evaporative heat loss are facilitated by air exchange through clothing [1]. The air permeability in COT was by far the highest of all fabrics. However, its permeability may not sustain well in a wet state. Cotton fibers swell when they become wet [29], which reduces the interstices in the fabric, thereby inhibiting air flow [33].

Results of the WVTR test, specifically with the type of test used in this study (ASTM E96), have been shown to be largely influenced by fabric thickness [24]. Havenith [28] also mentioned that water vapor resistance increases for thicker fabrics. Surprisingly, COT and

POLY did not have significantly higher WVTR values, considering they were the thinnest fabrics. However, it may have been due to their knit structures. Overall, the thermal insulation, air permeability, and moisture vapor transport capabilities of fabrics are more dependent upon a fabric's construction than its fiber properties [24, 77].

COT and POLY performed as expected for the moisture wicking test (Figures 6 and 7). Cotton, a natural fiber, is hydrophilic, meaning it readily absorbs and retains water [29]. Wetting causes cotton to swell, which changes the fabric's capillary space position [44]. Therefore, its ability to wick moisture is very poor. This observation has been confirmed in other studies examining natural fibers [42, 43]. Polyester and spandex, which are synthetic fibers, are more hydrophobic, possessing a greater ability to wick moisture than natural fibers [29, 43]. Additionally, polyester is often treated with hydrophilic chemical finishes in sportswear garments to improve its moisture transport capabilities [37, 70]. As shown in Figures 6 and 7, the wicking height for COT was negligible, while the wicking height for POLY rose rapidly over the first 10 minutes and then steadily increased every 10 minutes thereafter. Another factor to note is the difference in pore sizes between COT and POLY. In a study by Yanilmaz and Kalaoglu [47], pore size and wicking height were inversely related, in which fabrics with larger pores had lower wicking heights than those with smaller pores. Fabrics with smaller pores possess a higher capillary pressure, causing liquid to transfer over a greater distance. When examining the pore sizes between COT and POLY in Figure 1, it can be inferred that the smaller pore sizes in POLY also played a major role in its superior wicking performance.

NEW-J and NEW-P performed very similarly in terms of their vertical wicking ability. Both fabrics wicked moisture much more slowly than POLY, which may have been due largely in part to their knit structures. As observed in Figure 1, NEW-J and NEW-P appear to be tightly knitted. Tighter fabrics possess higher contact angles than slack fabrics, making their surfaces more compact [47]. As a result, wicking rates are lower in fabrics with high contact angles [44]. These results fall in line with the findings of Fangueiro et al. [44] and Yanilmaz and Kalaoglu [47]. The nylon content of NEW-J and NEW-P may have also been another factor contributing to their lower wicking values, as nylon fibers also have greater moisture regain than polyester [29].

Conclusion

Overall, the thermal and moisture management performance of the fabrics in this study appears to have been due to their fabric construction more than their fiber properties alone. This finding has been confirmed in other studies as well [24, 31, 38, 44, 77]. Further research should be conducted to examine other thermal comfort properties of the fabrics, such as drying time. The amount of time required for a garment to dry while being worn is important in maintaining comfort, as it deals with the ability of sweat to evaporate from the fabric [34]. The thermal comfort properties examined in this study, specifically water vapor transport and wicking ability, can also be analyzed using other test methods. The sweating guarded hot plate is an indirect method of measuring the moisture vapor transport property of fabrics. It simulates moisture transport through textiles worn next to the human skin [33], and it provides measures of water vapor resistance and thermal resistance [78]. Other methods for measuring wicking ability include in-plane wicking, as used in the study by Fangueiro et al. [44], and transplanar or transverse wicking. The transverse wicking test has been used to simulate the wicking of moisture from sweating skin through the thickness of a fabric [79].

It is also important to note that the experimental procedures used in this study were steady-state procedures, which are inadequate in fully examining the heat and moisture management capabilities of fabrics [33]. The human body is predominantly in a transient state, especially during physical activity and when exposed to different climatic conditions [4]. Therefore, fabric performance should also be explored under transient states, using human experimental protocols, in order to gain a more thorough understanding of their comfort capabilities [45]. A follow-up study using human subjects was conducted by the author to examine the effects of the fabrics in this study on measures of thermophysiology and comfort while performing a cycling protocol in a hot, dry environment.

References

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

4. Li, Y., *The science of clothing comfort.* Textile Progress, 2001. **31**(1-2): p. 1-135.

5. Pascoe, D.D., Shanley, L.A., and Smith, E.W., *Clothing and exercise. I: Biophysics of heat transfer between the individual, clothing and environment.* Sports Med, 1994. **18**(1): p. 38-54.

8. Thein, L.A., *Environmental conditions affecting the athlete.* J Orthop Sports Phys Ther, 1995. **21**(3): p. 158-71.

9. Pascoe, D.D., Bellingar, T.A., and McCluskey, B.S., *Clothing and exercise. II. Influence of clothing during exercise/work in environmental extremes.* Sports Med, 1994. **18**(2): p. 94-108.

13. Davis, J.K. and Bishop, P.A., *Impact of Clothing on Exercise in the Heat.* Sports Med, 2013.

16. Gavin, T.P., *Clothing and thermoregulation during exercise.* Sports Med, 2003. **33**(13): p. 941-7.

18. Gleeson, M., *Temperature regulation during exercise.* International Journal of Sports Medicine, 1998. **19**: p. S96-S99.

20. Bross, M.H., Nash, B.T., Jr., and Carlton, F.B., Jr., *Heat emergencies.* Am Fam Physician, 1994. **50**(2): p. 389-96, 398.

22. Gonzalez-Alonso, J., Teller, C., Andersen, S.L., Jensen, F.B., Hyldig, T., and Nielsen, B., *Influence of body temperature on the development of fatigue during prolonged exercise in the heat.* Journal of Applied Physiology, 1999. **86**(3): p. 1032-1039.

24. Prahsarn, C., Barker, R.L., and Gupta, B.S., *Moisture vapor transport behavior of polyester knit fabrics.* Textile Research Journal, 2005. **75**(4): p. 346-351.

26. Nagata, H., *Evaporative heat loss and clothing.* J Hum Ergol (Tokyo), 1978. **7**(2): p. 169-75.

27. Li, Y., *Perceptions of temperature, moisture and comfort in clothing during environmental transients.* Ergonomics, 2005. **48**(3): p. 234-48.

28. Havenith, G., *The Interaction between clothing insulation and thermoregulation.* Exogenous Dermatology, 2002. **1**(5): p. 221-230.

29. Kadolph, S.J., *Textiles.* 10 ed. 2007, Upper Saddle River, NJ: Pearson Education, Inc.

30. Gavin, T.P., Babington, J.P., Harms, C.A., Ardelt, M.E., Tanner, D.A., and Stager, J.M., *Clothing fabric does not affect thermoregulation during exercise in moderate heat.* Med Sci Sports Exerc, 2001. **33**(12): p. 2124-30.

31. Oglakcioglu, N. and Marmarali, A., *Thermal comfort properties of some knitted structures.* Fibres & Textiles in Eastern Europe, 2007. **15**(5-6): p. 94-96.

32. Hes, L. and Loghin, C., *Heat, moisture and air transfer properties of selected woven fabrics in wet state.* Journal of Fiber Bioengineering and Informatics, 2009. **2**(3): p. 141-149.

33. Das, B., Das, A., Kothari, V.K., Fangueiro, R., and de Araujo, M., *Moisture transmission through textiles part ii: Evaluation methods and mathematical modelling.* AUTEX Research Journal, 2007. **7**(3): p. 194-216.

34. Laing, R.M., Wilson, C.A., Gore, S.E., and Carr, D.J., *Determining the drying time of apparel fabrics.* Textile Research Journal, 2007. **77**(8): p. 583-590.

36. Ueda, H. and Havenith, G., *The effect of fabric air permeability on clothing ventilation*, in *Environmental Ergonomics - The Ergonomics of Human Comfort, Health and Performance in the Thermal Environment*, Y. Tochihara and T. Ohnaka, Editors. 2005, Elsevier B. V. p. 343-346.

37. Yoo, S. and Barker, R.L., *Moisture management properties of heat-resistant workwear fabrics - Effects of hydrophilic finishes and hygroscopic fiber blends.* Textile Research Journal, 2004. **74**(11): p. 995-1000.

38. Saricam, C. and Kalaoglu, F., *Investigation of the Wicking and Drying Behaviour of Polyester Woven Fabrics.* Fibres & Textiles in Eastern Europe, 2014. **22**(3): p. 73-78.

40. Simile, C., *Critical evaluation of wicking in performance fabrics*, in *School of Polymer, Textile, and Fiber Engineering*. 2004, Georgia Institute of Technology. p. 79.

42. Dai, X.Q., Imamura, R., Liu, G.L., and Zhou, F.P., *Effect of moisture transport on microclimate under T-shirts.* Eur J Appl Physiol, 2008. **104**(2): p. 337-40.

43. Das, B., Das, A., Kothari, V., Fanguiero, R., and Araujo, M.D., *Moisture Flow through Blended Fabrics - Effect of Hydrophilicity.* Journal of Engineered Fibers and Fabrics, 2009. **4**(4): p. 20-28.

44. Fangueiro, R., Filgueiras, A., Soutinho, F., and Xie, M.D., *Wicking Behavior and Drying Capability of Functional Knitted Fabrics.* Textile Research Journal, 2010. **80**(15): p. 1522-1530.

45. Bedek, G., Salaun, F., Martinkovska, Z., Devaux, E., and Dupont, D., *Evaluation of thermal and moisture management properties on knitted fabrics and comparison with a physiological model in warm conditions.* Appl Ergon, 2011. **42**(6): p. 792-800.

47. Yanilmaz, M. and Kalaoglu, F., *Investigation of wicking, wetting and drying properties of acrylic knitted fabrics.* Textile Research Journal, 2012. **82**(8): p. 820-831.

48. Bouskill, L.M., Havenith, G., Kuklane, K., Parsons, K.C., and Withey, W.R., *Relationship between clothing ventilation and thermal insulation.* Aihaj, 2002. **63**(3): p. 262-268.

57. Wickwire, J., Bishop, P.A., Green, J.M., Richardson, M.T., Lomax, R.G., Casaru, C., Curther-Smith, M., and Doss, B., *Physiological and comfort effects of commercial "wicking"*

clothing under a bulletproof vest. International Journal of Industrial Ergonomics, 2007. **37**(7): p. 643-651.

69. Kicklighter, T.H., Edsall, J.R., and Martin, M., *Effect of Moisture-Wicking Garments on Temperature Regulation During Exercise.* International Journal of Athletic Therapy & Training, 2011. **16**(6): p. 9-13.

70. Holme, I., *Innovative technologies for high performance textiles.* Coloration Technology, 2007. **123**(2): p. 59-73.

71. Havenith, G., Heus, R., and Lotens, W.A., *Clothing Ventilation, Vapor Resistance and Permeability Index - Changes Due to Posture, Movement and Wind.* Ergonomics, 1990. **33**(8): p. 989-1005.

72. Chi, T. and Kilduff, P., *Understanding consumer perceived value of casual sportswear: An empirical study.* Journal of Retailing and Consumer Services, 2011. **18**: p. 422-429.

73. Hes, L. and Dolezal, I., *New method and equipment for measuring thermal properties of textiles.* Journal of the Textile Machinery Society of Japan, 1989. **42**(8): p. 124-128.

74. American Society for Testing and Materials, *ASTM D737, Standard Test Method for Air Permeability of Textile Fabrics*. 2012, ASTM International: West Conshohocken, PA.

75. American Society for Testing and Materials, *ASTM E96, Standard Test Methods for Water Vapor Transmission of Materials*. 2013, ASTM International: West Conshohocken, PA.

76. American Association of Textile Chemists and Colorists, *AATCC TM 197, Vertical Wicking of Textiles*. 2013, American Association of Textile Chemists and Colorists: Research Triangle Park, NC.

77. Yoon, H.N. and Buckley, A., *Improved Comfort Polyester .1. Transport-Properties and Thermal Comfort of Polyester Cotton Blend Fabrics.* Textile Research Journal, 1984. **54**(5): p. 289-298.

78. Huang, J.H., *Sweating guarded hot plate test method.* Polymer Testing, 2006. **25**(5): p. 709-716.

79. Harnett, P.R. and Mehta, P.N., *A Survey and Comparison of Laboratory Test Methods for Measuring Wicking.* Textile Research Journal, 1984. **54**(7): p. 471-478.

IV. JOURNAL MANUSCRIPT 2

Introduction

The ability of the human body to maintain thermal balance in hot environments is of great importance, as prolonged exposure to hot environments can increase the risk of heat illness and heat injury [7, 8, 20]. It is even more pivotal during periods of physical activity, as the combination of metabolic heat production and heat gain from the external environment causes greater rises in body temperature [18]. Our bodies dissipate heat via means of conduction, convection, radiation, and evaporation in order to maintain thermal balance [16], with the evaporation of sweat serving as the most effective mechanism of heat dissipation during physical activity [1, 15]. Clothing impedes the transfer of evaporative heat from the body to the external environment [5, 18, 26]. As a result, bodily heat storage continues to increase and wearer comfort is compromised [4, 9].

In recent decades, several clothing manufacturers have engineered garments in the sports apparel market with the aim of alleviating heat stress and improving wearer comfort for active individuals. Different materials and technologies are incorporated into these garments, including synthetic fabric blends, fabric channels, and ventilation panels. These garments are purported to have superior heat and moisture management properties, such as the ability to "wick" sweat, to keep wearers cooler, dryer, and more comfortable in hot environments [9, 30, 69]. However, these claims have not been well-founded by research [13].

Several studies have analyzed the thermophysical and comfort properties of sportswear fabrics using non-human [2, 40, 41, 44, 50-52] and human methodologies. Of those using human methods, protocols consisting of ≤ 60 minutes of exercise are generally used [30, 55, 56, 59, 61, 65], and a limited number have been conducted in environments ≥ 30°C [23, 30, 57, 58, 62, 65]. Gavin et al. [30] tested a synthetic clothing ensemble claimed to promote sweat evaporation versus a cotton ensemble on males during an exercise bout consisting of 15 minutes seated rest, 30 minutes running at 70% VO_2max, 15 minutes walking at 40% VO_2max, and 15 minutes seated rest. They found no differences in physiological, thermoregulatory, or comfort sensation responses between garment types. In addition, only a few studies [64, 65, 80] have analyzed the effects of sportswear garments on performance variables (e.g., time trial completion or exercise until fatigue). Park et al. [80] found high school baseball players pitched faster balls in a hot environment when wearing cotton compared to polyester and polypropylene.

The production of sportswear has been a successful enterprise in the 21st century, and the demand for them continues to increase [81]. There remains a need to assess the effects of these garments on thermoregulation and comfort using valid human testing. Furthermore, there is a need for research studies that examine these effects with exercise protocols of moderate to high intensity lasting more than 60 minutes, as well as studies examining the effects of sportswear on performance variables [13].

The purpose of this study was to analyze the effects of a prototype for a new sportswear shirt on thermophysiological and subjective measures while cycling in a hot environment. The garment, which was designed for males, was compared to two other commercially produced sportswear shirts designed for hot environments. The information gained in this study will be beneficial to the manufacturer of the garment prototype to determine if further modifications or improvements to the garment are necessary prior to its mass production.

Methods

Garments

The garment prototype (NEW) examined in this study consisted of a 90/10 nylon/spandex fiber blend. As shown in Figure 1, the garment design consisted of jersey and pique knit structures. The pique knit, which has greater air permeability, was placed in regions of the body containing high sweat rates as observed in previous research by Havenith et al. [82], and Smith and Havenith [83]. It was expected that a greater exchange of air flow in these areas would facilitate evaporative and convective heat loss to attenuate heat storage and improve thermal comfort [61, 84-86]. The jersey and pique knits were separated by a seamless transition in order to promote greater fit [87] and to prevent discomfort often caused by the rubbing of stitches and seams [4].

The other commercial sportswear shirts tested included an 84/16 polyester/spandex blended shirt (POLY) and a 100% cotton shirt (COT). Both garments were sleeveless and fit next-to-skin just as the NEW garment. The physical and thermal characteristics of the all fabrics tested in the study are presented in Table 1. All garments used for each trial were white in color and were in brand new condition.

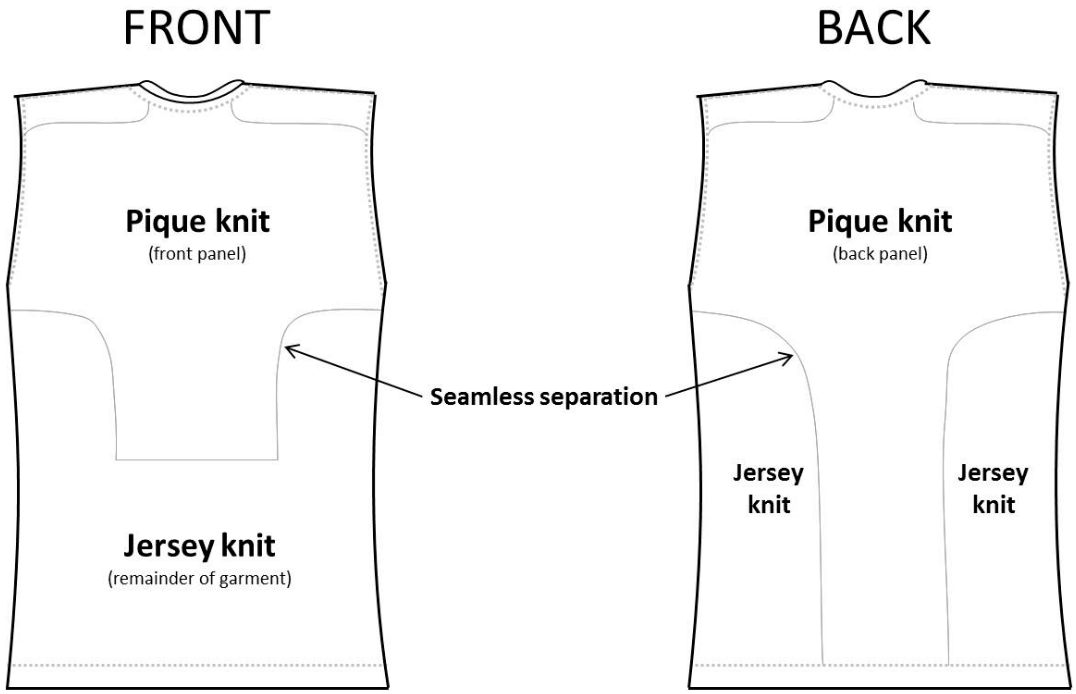


Figure 1. Sketch of Garment Design

Table 1. Physical and Thermal Properties of Garment Fabrics

Property	**Fabric**			
	COT	POLY	NEW (jersey knit)	NEW (pique knit)
Brand	*Fruit of the Loom®*	*BCG™*	*Russell Athletic™*	*Russell Athletic™*
Fiber content	100% cotton	84% polyester 16% spandex	90% nylon 10% spandex	90% nylon 10% spandex
Knit structure	Single jersey	Single jersey	Single jersey	Pique
Thickness (mm)	0.58	0.5	0.91	1.11
Courses (#/cm)	20	32	24	8
Wales (#/cm)	14	21	15	5
Thermal conductivity (W/(m·K))	0.042 ± 0.001	0.045 ± 0.001	0.057 ± 0.001	0.048 ± 0.001
Thermal resistance ((K·m²)/W)	0.013 ± 0.000	0.011 ± 0.000	0.016 ± 0.000	0.023 ± 0.000
Air permeability (ft³/min/ft²)	216.2 ± 16.8	91.9 ± 4.3	42.2 ± 1.8	103.9 ± 3.9

WVTR ($g/m^2/24h$)	569.8 ± 7.5	586.5 ± 27.6	572.0 ± 15.9	613.3 ± 29.4
Vertical wicking ht. @ 10 min. (cm)	0.0	11.9	2.8	2.3
Vertical wicking ht. @ 60 min. (cm)	0.1	19.4	3.9	2.9

Participants

Twelve healthy, active males volunteered to participate in this study. Participants were included in the study according to the following criteria: 1) between 19 – 35 years of age; 2) healthy, as determined by PAR-Q medical screening (Appendix B); 3) oxygen uptake max (VO_2max) of > 35 ml/kg/min, which demonstrates moderate aerobic fitness. Descriptive data for the participants is shown in Table 2.

Table 2. Participant Descriptive Data (n = 12)

Variable	Mean ± SD	Minimum	Maximum
Age (yrs)	22.6 ± 2.5	20	27
Height (in)	71.4 ± 2.9	67	76
Weight (kg)	80.6 ± 9.1	70.8	96.3
Body fat (%)	17.7 ± 4.4	14.1	27.9
VO_2max (ml/kg/min)	50.5 ± 7.8	37.4	65.5

Preliminary Procedures

The study was approved by the Institutional Review Board at Auburn University prior to any data collection procedures were performed. Participants arrived to the Kinesiology Thermal Regulation Lab for their initial visit, which involved reading and signing the institutionally approved informed consent document (Appendix A). They then had their body composition assessed by dual x-ray absorptiometry (iDEXA, General Electric; Fairfield, CT).

Upon their second visit to the lab, each participant performed a VO_2max test on an electronic bicycle ergometer (Velotron, RacerMate Inc.; Seattle, WA) to assess maximal aerobic capacity. The workload began at 100 W for the first stage and increased by 25 W each stage. The first stage lasted five minutes, the second and third stages each lasted three minutes, and every stage thereafter lasted one minute. Tests ended once the participant could no longer maintain a pedaling cadence of at least 60 rpm or once they signaled to end the test. Respiratory gases were analyzed via open-circuit spirometry using an automated metabolic testing system (TrueOne 2400 Metabolic Measuring System, Parvo Medics, Inc.; Provo, UT). VO_2max was determined as the highest observed oxygen uptake average over one minute if there was no rise in VO_2 with increasing workload, the respiratory exchange ratio was > 1.15, heart rate was within 10 beats per minute (bpm) of the age-predicted maximum, or the participant reached volitional exhaustion.

Experimental Procedures

Participants performed a total of six trials consisting of the following: three (3) heat acclimation trials and three (3) randomized trials. All trials were performed in a controlled environmental chamber (Espec North America, Inc.; Hudsonville, MI) in the Thermal Regulation Lab. Chamber conditions were set at 35°C, 40% RH, with a 2 m/s air velocity. Each participant wore athletic clothing of their choice for all trials; however, the three treatment shirts were provided for the randomized trials. Upon arriving to the lab, a urine sample was collected for each participant to determine hydration status. Samples were assessed for urine specific gravity using a refractometer (Atago Co.; Tokyo, Japan). Participants were allowed to perform the trial if their urine specific gravity was ≤ 1.020 g/ml. Nude body weights were also measured before and after each trial on a calibrated scale to help calculate sweat loss. Trials were performed at the same time of day to avoid any thermal or performance effects from circadian rhythms.

Criteria for trial termination included the following: 1) rectal core temperature of at least 39.5°C; or 2) participant volitionally stopped.

Acclimation Trials

Prior to the randomized trials, participants completed three acclimation trials to evaluate work effort and acclimation response in the prescribed chamber conditions. All trials were completed within a week period, with no less than 24 hours between each trial. Participants were allowed to drink water ad libitum, and water bottles were weighed before and after each trial to help calculate sweat loss (along with the pre-post body weight differences).

For the first two trials, each participant cycled for 90 minutes on the electronic bicycle ergometer at 40% of their VO_2max workload, which was the same workload percentage used by Robinson et al. [88] in a study assessing rapid acclimatization to work in hot climates. Participants were asked to maintain a pedaling cadence of at least 60 rpm. Measures of heart rate (HR), core temperature (T_c), and rating of perceived exertion (RPE) were monitored and recorded every five minutes for the entire trial. HR was measured using a monitor strapped around each participant's chest (Polar Electro Inc.; Lake Success, NY). T_c was measured with a temperature probe (YSI 4000A, YSI Inc.; Dayton, OH) inserted 10 cm beyond the anal sphincter. RPE was recorded using the 15-point Borg scale (APPENDIX C) [89].

The third acclimation trial acted as a protocol familiarization trial, in which each participant performed the same cycling protocol as in the randomized trials. The contents of the cycling protocol will be explained in the following section.

Randomized Trials

The three shirts (NEW, POLY, and COT) were assigned randomly to each participant for the experimental trials. All trials were completed with no less than 24 hours in between, and participants were asked to refrain from strenuous physical activity in the 24 hours leading up to each trial. Participants wore similar shoes, socks, shorts, and underwear for all trials. Water consumption for each participant was matched to the amount consumed in the first randomized trial. As before, water bottles were weighed before and after each trial to help calculate sweat loss. Shirts were also weighed before and after each trial to analyze the absorbency and moisture retention properties between each shirt type.

Prior to beginning the cycling protocol, each participant went through a 15-minute equilibration period in a controlled laboratory environment (23°C; 50% RH) while shirtless. Immediately following the equilibration, infrared images were taken of the front and back torso region with an infrared camera (CTI™ Thermal Imaging Processor). Participants then put on their assigned shirt and the same procedure was repeated. These images were taken to examine the pre-post thermal profiles of each shirt.

The cycling protocol consisted of a 45-minute bout in which each participant cycled at 50% of their VO_2max workload (maintaining at least 60 rpm), followed by a 12-mile time trial which was completed using a simulated course created in the Velotron 3D computer software.

Physiological Measures. HR, T_c, and torso skin temperature ($T_{sktorso}$) were recorded at the beginning and every five minutes throughout the 45-minute bout. HR and T_c were measured by the same means as described earlier. $T_{sktorso}$ was measured using thermocouples taped at the chest and the back (Squirrel SQ 2020 Series Data Logger, Grant Instruments; Shepreth, United Kingdom). Mean $T_{sktorso}$ was calculated according to the following equation used by Davey et al. [90]:

$$T_{sktorso} = 0.5T_{chest} + 0.5T_{back}$$

Use of two sites for determining mean torso skin temperature is further justified by Livingstone et al. [91], who found lower variances in skin temperature isotherms on the torso during high ambient temperatures.

Only HR and T_c were monitored during the 12-mile time trial for safety purposes, in order to ensure participants did not meet any criteria for trial termination as stated above.

Subjective Measures. Ratings of thermal sensation, thermal comfort, and wetness sensation were recorded using a 10 cm line, in which subjects marked a specific spot on the line indicative of their response for the particular rating (Appendix D). The scale for thermal sensation ranged from "neutral" to "very hot," the thermal comfort scale ranged from "comfortable" to "extremely uncomfortable," and wetness sensation ranged from "dry" to "very wet." Ratings were recorded immediately before the 45-minute bout, every 15 minutes during the bout, immediately following the bout, and immediately following the completion of the 12-mile time trial. RPE was also recorded every five minutes during the 45-minute cycling bout.

Statistical Analysis

All data are presented as mean ± SD. A 3 (shirt) x 4 (time) two-way ANOVA with repeated measures for both shirt and time was used to compare T_c, $T_{sktorso}$, and HR. If there was a significant interaction, pairwise comparisons between shirts were made at each time point. A one-way ANOVA with repeated measures was used to compare ΔT_c, sweat loss (as % body weight), and Δ shirt weight, and pairwise comparisons were made between the shirts. The 12-mile trial performance times were analyzed using a one-way ANOVA due to the different sample sizes between the shirts (the reason for the unequal sample sizes will be further explained in the next section). Ratings of thermal sensation, thermal comfort, and wetness sensation were all compared using a 3 (shirt) x 5 (time) two-way ANOVA with repeated measures for both shirt and time, while RPE was analyzed using a 3 (shirt) x 8 (time) two-way ANOVA with repeated measures. Pairwise comparisons between shirts were made at each time point if there was a significant interaction. The level of significance for statistical tests was set at $p \leq .05$. However, all P values have been presented for the sake of apparel marketers and manufacturers who may recognize the importance of less stringent statistical values. All statistical tests were carried out using SPSS Statistics Version 22 (IBM Corp.; Chicago, IL).

Results

Thermophysiological Responses

All thermophysiological data are presented in Table 3. No significant shirt main effects were found for T_c ($p = .07$), $T_{sktorso}$ ($p = .66$), or HR ($p = .8$). Also, no significant differences were observed between shirts for ΔT_c ($p = .25$) and sweat loss ($p = .87$). The Δ shirt weight was significantly higher ($p < .001$) for NEW compared to both COT and POLY. Concerning 12-mile time trial performance, data were analyzed with n = 9 for POLY and n = 11 for both COT and NEW due to subjects reaching the trial cutoff point of 39.5°C core temperature. Performance times were not different between shirts ($p = .11$).

Table 3. Thermophysiological Data between Shirts (n = 12)

	Shirt		
Variable	COT	POLY	NEW
Core temperature (°C)			
Pre	37.44 ± 0.21	37.43 ± 0.28	37.25 ± 0.24
15 min.	37.78 ± 0.20	37.79 ± 0.27	37.68 ± 0.19
30 min.	38.06 ± 0.24	38.12 ± 0.29	37.99 ± 0.22
Post 45 min.	38.29 ± 0.31	38.39 ± 0.40	38.19 ± 0.24
Δ	0.84 ± 0.28	0.96 ± 0.28	0.94 ± 0.28
Torso skin temperature (°C)			
Pre	33.35 ± 2.66	33.76 ± 1.96	32.83 ± 1.63
15 min.	35.11 ± 1.52	35.03 ± 0.82	34.77 ± 1.02
30 min.	35.30 ± 1.23	34.90 ± 0.68	35.04 ± 0.76
Post 45 min.	35.45 ± 1.12	34.85 ± 0.90	35.19 ± 0.59
Heart rate (bpm)			
Pre	81 ± 10	79 ± 13	76 ± 11
15 min.	141 ± 12	141 ± 12	140 ± 10
30 min.	147 ± 16	146 ± 15	146 ± 10
Post 45 min.	137 ± 26	139 ± 20	137 ± 18
Sweat loss (% body weight)	2.97 ± 0.37	2.91 ± 0.41	2.98 ± 0.58
Δ Shirt weight (g)	132.6 ± 27.0	138.9 ± 32.7	203.4 ± 51.0*
12-mile time trial (sec)§	2321 ± 170	2301 ± 162	2286 ± 151

Values are reported as means ± SD.
* Denotes NEW significantly different from COT (*p* < .001) and POLY (*p* < .001).
§ Denotes difference in sample sizes for 12-mile time trial between COT (n = 11), POLY (n = 9), and NEW (n = 11).

T_c responses throughout the 45-minute cycling bout are shown in Figure 2. Measures of core temperature provide a valid assessment of the amount of heat stored in the body. An effective garment will alleviate rises in T_c. Although results between shirts were not significant (*p* = .07), a trend of lower measures was seen in NEW.

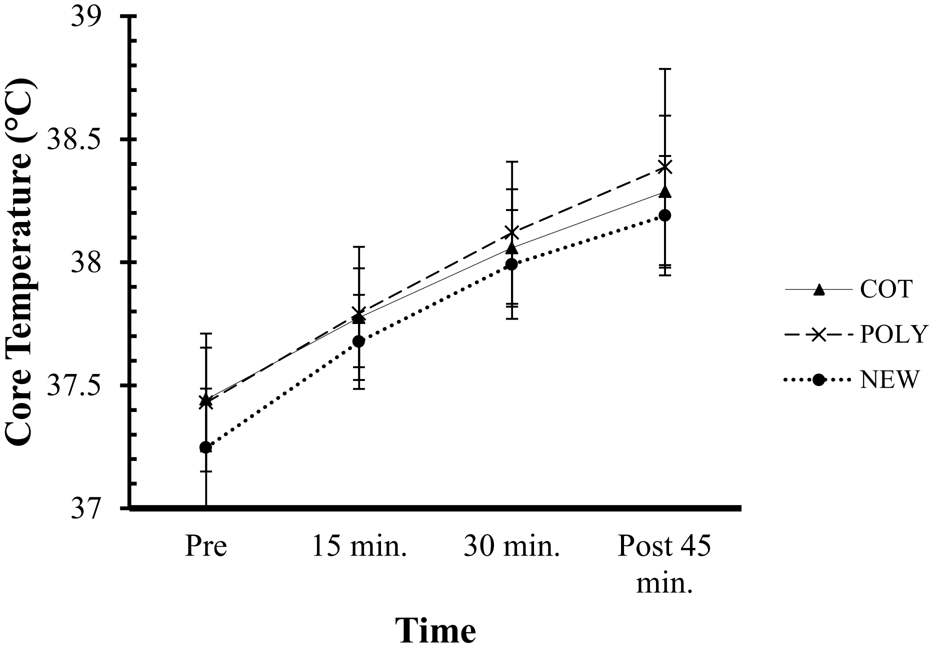


Figure 2. Core Temperature between Shirts. Values are reported as means ± SD. No significant main effects were found between shirts.

$T_{sktorso}$ responses throughout the 45-minute cycling bout are shown in Figure 3. Skin temperatures may fluctuate depending on metabolic heat production and the interactions between the skin, clothing, and ambient environment. Measures of $T_{sktorso}$ were similar between shirts.

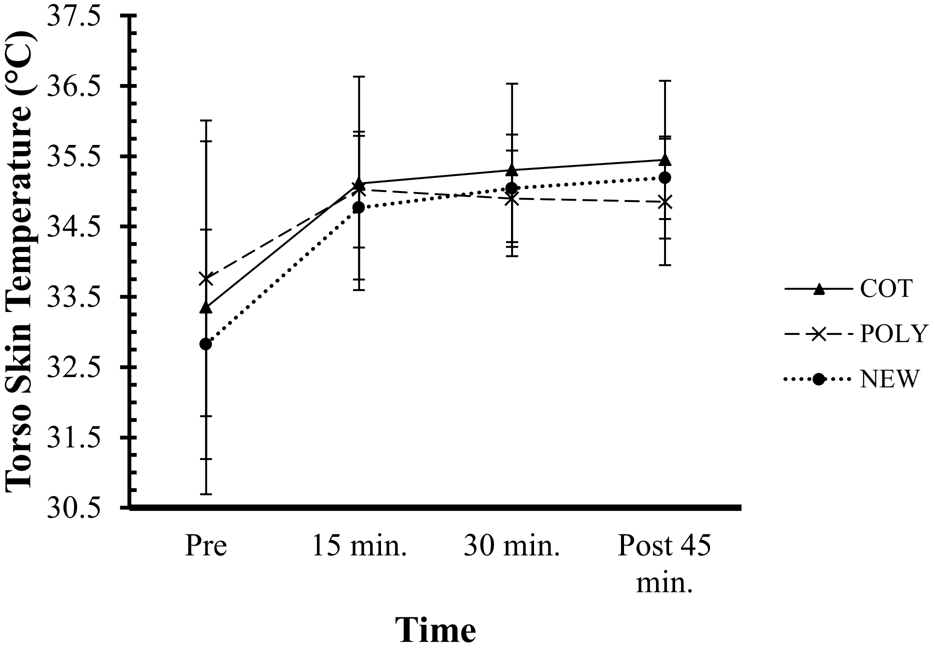


Figure 3. Torso Skin Temperature between Shirts. Values are reported as means ± SD. No significant main effects were found between shirts.

Subjective Responses

Data for all subjective responses are presented in Table 4, which also includes a visual of the scales used for thermal sensation, thermal comfort, and wetness sensation. Results from the two-way ANOVA yielded a significant interaction between shirt and time for thermal sensation ($p < .001$), thermal comfort ($p < .01$), and wetness sensation ($p < .001$). However, there was no significant interaction or shirt effect for RPE ($p = .64$).

Table 4. Subjective Data between Shirts (n = 12)

	Shirt		
Variable	COT	POLY	NEW
Thermal Sensation (cm)*			
	Neutral 0 cm		Very Hot 10 cm
Pre	1.0 ± 1.0	1.2 ± 0.8	0.7 ± 0.7
15 min.	3.4 ± 1.3	3.3 ± 1.4	2.2 ± 1.3
30 min.	4.9 ± 1.8	4.4 ± 1.7	3.0 ± 1.0
Post 45 min.	6.0 ± 2.0	5.0 ± 1.7	3.6 ± 1.0
Post Time Trial	7.9 ± 2.2	7.3 ± 1.9	4.9 ± 1.7
Thermal Comfort (cm)*			
	Comfortable 0 cm		Extremely Uncomfortable 10 cm
Pre	1.2 ± 1.8	1.0 ± 1.0	0.2 ± 0.5
15 min.	3.5 ± 2.0	2.6 ± 1.4	2.1 ± 1.3
30 min.	5.4 ± 2.7	3.7 ± 1.6	2.6 ± 1.4
Post 45 min.	6.3 ± 2.4	4.4 ± 1.9	2.9 ± 1.6
Post Time Trial	7.3 ± 2.2	5.6 ± 2.0	4.2 ± 1.9
Wetness Sensation (cm)*			
	Dry 0 cm		Very Wet 10 cm
Pre	0.0 ± 0.1	0.2 ± 0.5	0.0 ± 0.0
15 min.	3.8 ± 1.9	3.1 ± 1.8	1.7 ± 0.9
30 min.	6.2 ± 2.4	4.5 ± 2.3	3.1 ± 1.3
Post 45 min.	7.4 ± 2.3	6.3 ± 2.8	3.8 ± 1.5
Post Time Trial	8.8 ± 1.9	7.9 ± 2.2	5.2 ± 1.7
Rating of Perceived Exertion			
5 min.	10 ± 2	10 ± 2	10 ± 2
10 min.	11 ± 2	10 ± 2	10 ± 2
15 min.	11 ± 2	11 ± 2	11 ± 2
20 min.	11 ± 2	11 ± 2	11 ± 2
25 min.	11 ± 2	11 ± 2	11 ± 2
30 min.	11 ± 2	11 ± 2	11 ± 2
35 min.	12 ± 2	12 ± 2	11 ± 1
40 min.	12 ± 1	12 ± 2	12 ± 1

Values are reported as means ± SD.
* Denotes significant interaction for thermal sensation ($p < .001$), thermal comfort ($p < .01$), and wetness sensation ($p < .001$).

Ratings of thermal sensation between shirts are shown in Figure 4. Thermal sensation refers to how hot the wearer's body feels in a particular garment. These sensations are mainly derived from sensory mechanisms in the skin, and they interact strongly with moisture sensations [4]. Pairwise comparisons revealed significantly better ratings of thermal sensation for NEW compared to both COT and POLY at 15 minutes ($p < .05$), 30 minutes ($p < .05$), and post time trial ($p < .001$ and $p < .01$, respectively). Additionally, NEW was significantly better than COT at the post 45-minute mark ($p < .01$). Thermal sensation ratings between COT and POLY were not different at any time point.

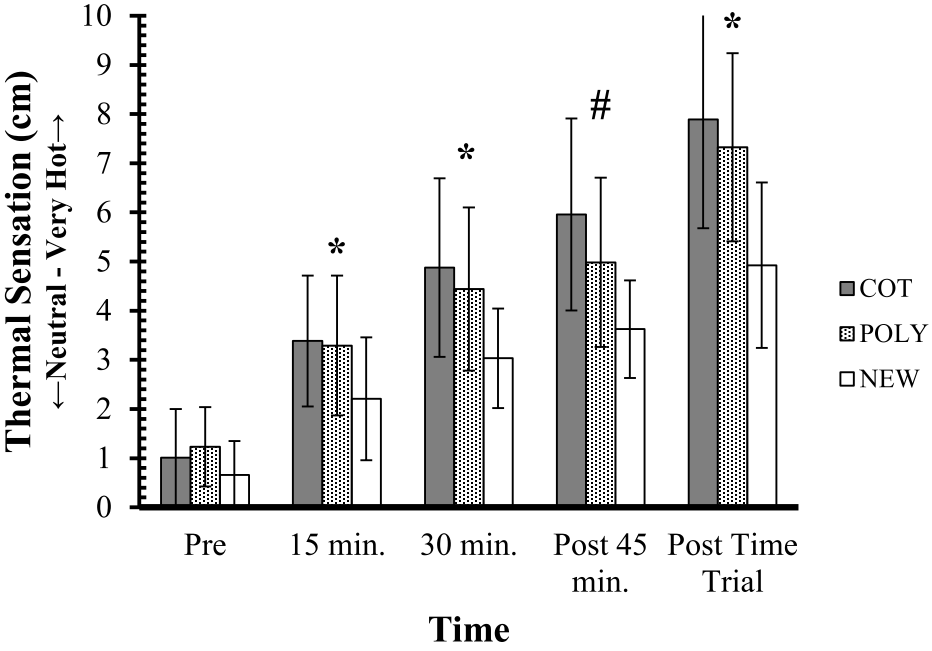


Figure 4. Ratings of Thermal Sensation between Shirts. Values are reported as means ± SD. * NEW significantly better than both COT and POLY at 15 minutes ($p < .05$), 30 minutes ($p < .05$), and post time trial ($p < .001$ and $p < .01$, respectively). # NEW significantly better than COT at post 45 minutes ($p < .01$).

Thermal comfort refers to how comfortable the wearer feels in a particular garment, which can depend on combinations of clothing, climate, and physical activity [4]. Concerning thermal comfort (Figure 5), NEW was significantly better than COT at 15 minutes (*p* < .05), 30 minutes (*p* < .05), post 45 minutes (*p* < .01), and post time trial (*p* < .01). Ratings between COT and POLY and between NEW and POLY were not different at any time point.

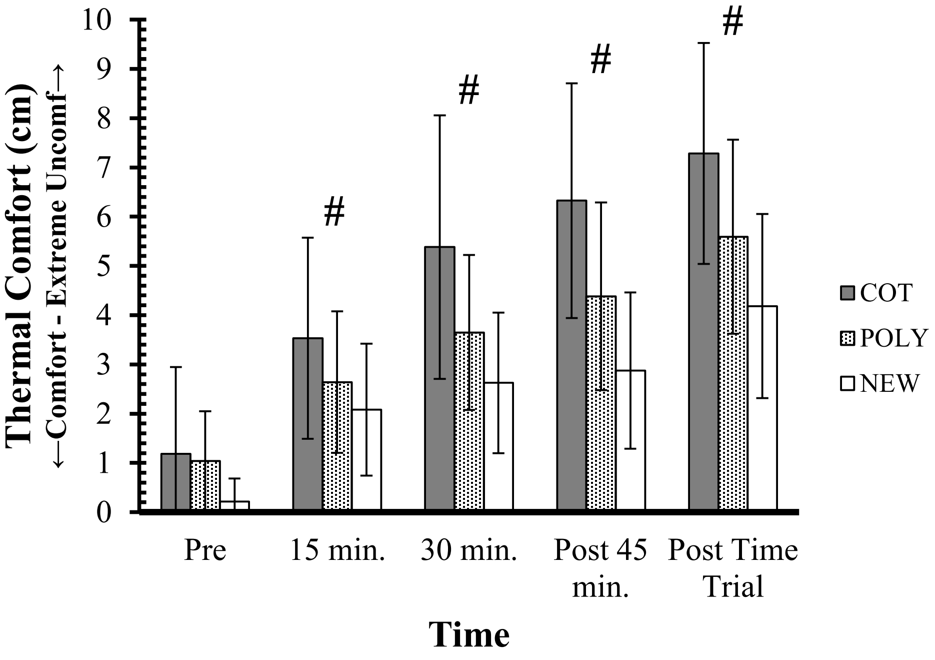


Figure 5. Ratings of Thermal Comfort between Shirts. Values are reported as means ± SD. # NEW significantly better than COT at 15 minutes (*p* < .05), 30 minutes (*p* < .05), post 45 minutes (*p* < .01), and post time trial (*p* < .01).

Wetness sensations can provide an indication of the humidity in the microclimate and the amount of moisture built up in the layer of clothing. Moisture in clothing is one of the most important factors promoting discomfort during wear [4]. Ratings of wetness sensation are displayed in Figure 6. Results indicated significantly better ratings for NEW compared to COT at 15 minutes (*p* < .01) and 30 minutes (*p* < .01). NEW was significantly better than both COT and POLY at post 45 minutes (*p* < .001 and *p* < .05, respectively) and post time trial (*p* < .01 and

$p < .05$, respectively). Wetness sensation ratings between COT and POLY were not different at any time point.

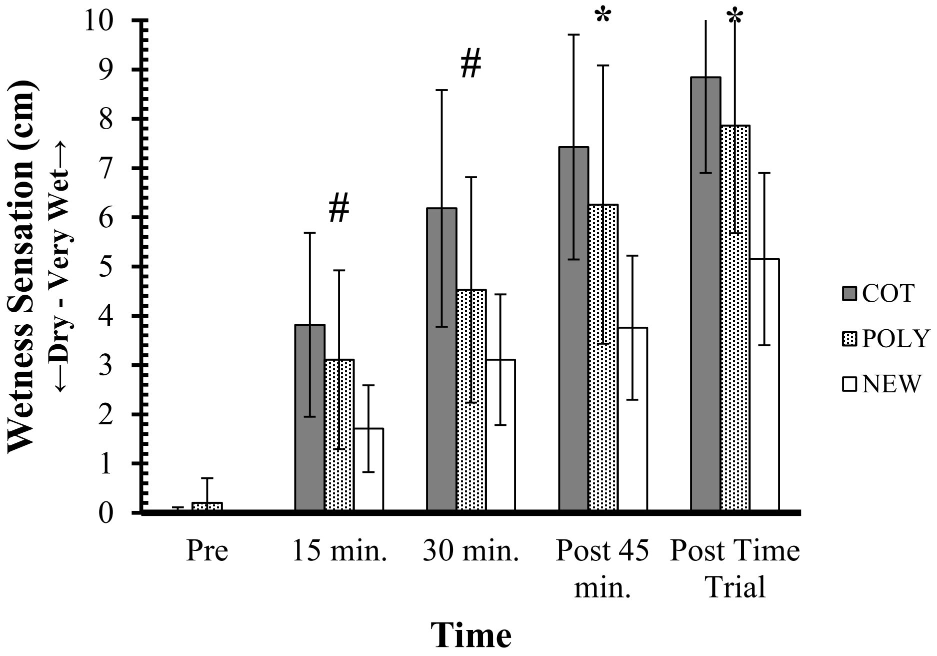


Figure 6. Ratings of Wetness Sensation between Shirts. Values are reported as means ± SD. * NEW significantly better than both COT and POLY at post 45 minutes ($p < .001$ and $p < .05$, respectively) and post time trial ($p < .01$ and $p < .05$, respectively). # NEW significantly better than COT at 15 minutes ($p < .01$) and 30 minutes ($p < .01$).

Discussion

The primary purpose of this study was to investigate the thermophysiological and subjective responses during cycling in a hot, dry environment when wearing a new prototype for a male sportswear shirt. The shirt was compared to two commercially produced sportswear shirts in its ability to provide thermoregulatory benefits and enhance markers of wearer comfort. No significant differences were found between shirts for several of the physiological components examined. However, subjective responses were more favorable for the garment prototype (NEW) than for the polyester and cotton shirts.

According to Davis and Bishop [13], no studies have incorporated an exercise protocol of moderate to high intensity lasting more than 60 minutes. Therefore, this study was one of the first to analyze the effects of clothing on measures of thermophysiology and comfort in a hot environment using an exercise protocol lasting more than 60 minutes and consisting of moderate and high-intensity bouts.

Thermophysiology and Performance

Measures of T_c, $T_{sktorso}$, and HR were not different between shirts at any time point. The amount of sweat loss as a percentage of body weight also was not different. When considering the textile fiber makeup of the shirts, these findings are consistent with several other studies showing no differences in thermophysiological variables between synthetic and cotton sportswear shirts during exercise [30, 55-65]. A controlled air velocity of 2 m/s was used in this study. It is worth mentioning that cycling in a real-life outdoor environment would generate significantly more airflow. This airflow would facilitate greater convective and evaporative heat loss [16], which may further attenuate rises in core and skin temperature.

The 12-mile trial performance times were also not different between shirts. However, it is important to note that three subjects were unable to complete the time trial for the POLY treatment due reaching the core temperature cutoff point of 39.5°C, compared to only one subject each for COT and NEW. Although POLY did not produce significantly higher core temperatures during the 45-minute cycling bout, it seemed to elicit a more rapid rise in core temperatures during the time trial. Very few studies [64, 65, 80] have examined the effects of sportswear clothing material on performance, and only one of them [80] found significantly greater measures of performance for natural compared to synthetic fabric. Despite these findings, the mean 12-mile trial completion time for NEW was 35 seconds faster than COT and 15 seconds faster than POLY. Though not faster in terms of statistical significance, these results may still translate well to real-life performance settings, where completion times between competitors are often separated merely by fractions of a second.

Comfort and Perception

The most remarkable findings in the present study were the differences in subjective responses between the shirts. Although synthetic fabrics have been shown to possess lower water regains than natural fabrics [59], this has not always led to greater comfort [13]. Perceptual ratings were not different between POLY and COT at any time point in this study, which falls in line with the findings from previous studies showing no significant differences in comfort [23, 30, 57-59, 61], thermal sensation [23, 57, 58, 61, 62], and skin wetness [23, 57, 58, 61] between synthetic and natural fabrics. Conversely, NEW was significantly better than COT, and at times better than both COT and POLY, on ratings of thermal sensation, thermal comfort, and wetness sensation the majority of the time.

Although the microclimate humidity of the shirts was not measured in this study, it's possible the lower thermal sensation in NEW may have been due to higher microclimate humidity in COT and POLY. Higher microclimate humidity hinders evaporative heat loss [28], which may cause sensations of increased warmth [61]. Ratings of thermal comfort were significantly lower in COT than in NEW. Cotton fibers gain mass as they become wet [29], causing the fabric to collapse against the body and consequently promoting discomfort.

Clothing wetness is one of the most important factors promoting discomfort during wear [4, 27]. Of the three shirts tested, NEW appeared to be the most hygroscopic, which refers to a fabric's ability to retain moisture without feeling wet [29].Although NEW retained the most sweat as denoted by its pre-to-post trial weight gain, it yielded the lowest ratings of wetness sensation of all shirts. Previous studies have shown that fabrics are perceived as less damp for those of greater hygroscopicity [92]. The fabric thickness and air permeability for NEW are also worth considering in regards to its lower ratings of wetness sensation. NEW's thickness, which was the greatest of all fabrics (Table 1), provided a longer distance through which the moisture from the sweat had to transport. This may have prevented it from feeling overly saturated. Also, the pique knit structure of NEW was more permeable to air than POLY (Table 1), allowing more air to flow through it. Studies by Prahsarn et al. [24] and Bedek et al. [45] have shown that fabrics with higher air permeability dry faster than those with lower air permeability. COT, despite having a very high air permeability in a dry state, is very absorbent to moisture [29]. Cotton fibers swell when they become wet, which reduces the size of the air spaces in the fabric and impedes the evaporation of moisture from the garment [41].

Conclusion

The aim of this study was to investigate the effects of a sportswear garment prototype versus two other commercially produced shirts on thermophysiological and subjective responses while cycling in a hot, dry environment. In summary, measures of thermophysiology were not significantly different between shirts. However, a trend of lower core temperatures was observed in NEW. The NEW shirt also elicited more favorable subjective responses. This study was one of the first to analyze the effects of clothing on measures of thermophysiology and comfort in a hot environment using an exercise protocol lasting more than 60 minutes and consisting of moderate and high-intensity bouts. Experimental protocols conducted in a more thermoneutral environment or using other types and/or intensities of physical activity may be of some benefit in order to further examine the effects of the new garment.

References

1. Havenith, G., *Heat balance when wearing protective clothing.* Ann Occup Hyg, 1999. **43**(5): p. 289-96.

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

4. Li, Y., *The science of clothing comfort.* Textile Progress, 2001. **31**(1-2): p. 1-135.

5. Pascoe, D.D., Shanley, L.A., and Smith, E.W., *Clothing and exercise. I: Biophysics of heat transfer between the individual, clothing and environment.* Sports Med, 1994. **18**(1): p. 38-54.

7. Binkley, H.M., Beckett, J., Casa, D.J., Kleiner, D.M., and Plummer, P.E., *National athletic trainers' association position statement: Exertional heat illnesses.* Journal of Athletic Training, 2002. **37**(3): p. 329-343.

8. Thein, L.A., *Environmental conditions affecting the athlete.* J Orthop Sports Phys Ther, 1995. **21**(3): p. 158-71.

9. Pascoe, D.D., Bellingar, T.A., and McCluskey, B.S., *Clothing and exercise. II. Influence of clothing during exercise/work in environmental extremes.* Sports Med, 1994. **18**(2): p. 94-108.

13. Davis, J.K. and Bishop, P.A., *Impact of Clothing on Exercise in the Heat.* Sports Med, 2013.

15. Brooks, G.A., Fahey, T.D., and Baldwin, K.M., *Excercise Physiology: Human Bioenergetics and Its Applications*. 4th ed. 2005, New York, NY: McGraw-Hill.

16. Gavin, T.P., *Clothing and thermoregulation during exercise.* Sports Med, 2003. **33**(13): p. 941-7.

18. Gleeson, M., *Temperature regulation during exercise.* International Journal of Sports Medicine, 1998. **19**: p. S96-S99.

20. Bross, M.H., Nash, B.T., Jr., and Carlton, F.B., Jr., *Heat emergencies.* Am Fam Physician, 1994. **50**(2): p. 389-96, 398.

23. Kwon, A., Kato, M., Kawamura, H., Yanai, Y., and Tokura, H., *Physiological significance of hydrophilic and hydrophobic textile materials during intermittent exercise in humans under the influence of warm ambient temperature with and without wind.* European Journal of Applied Physiology and Occupational Physiology, 1998. **78**(6): p. 487-493.

24. Prahsarn, C., Barker, R.L., and Gupta, B.S., *Moisture vapor transport behavior of polyester knit fabrics.* Textile Research Journal, 2005. **75**(4): p. 346-351.

26. Nagata, H., *Evaporative heat loss and clothing.* J Hum Ergol (Tokyo), 1978. **7**(2): p. 169-75.

27. Li, Y., *Perceptions of temperature, moisture and comfort in clothing during environmental transients.* Ergonomics, 2005. **48**(3): p. 234-48.

28. Havenith, G., *The Interaction between clothing insulation and thermoregulation.* Exogenous Dermatology, 2002. **1**(5): p. 221-230.

29. Kadolph, S.J., *Textiles*. 10 ed. 2007, Upper Saddle River, NJ: Pearson Education, Inc.

30. Gavin, T.P., Babington, J.P., Harms, C.A., Ardelt, M.E., Tanner, D.A., and Stager, J.M., *Clothing fabric does not affect thermoregulation during exercise in moderate heat.* Med Sci Sports Exerc, 2001. **33**(12): p. 2124-30.

40. Simile, C., *Critical evaluation of wicking in performance fabrics*, in *School of Polymer, Textile, and Fiber Engineering*. 2004, Georgia Institute of Technology. p. 79.

41. Yi, K.F., *Effect of heat and moisture transfer properties of t-shirts on comfort sensations*, in *Institute of Textiles and Clothing*. 2006, The Hong Kong Polytechnic University. p. 147.

44. Fangueiro, R., Filgueiras, A., Soutinho, F., and Xie, M.D., *Wicking Behavior and Drying Capability of Functional Knitted Fabrics.* Textile Research Journal, 2010. **80**(15): p. 1522-1530.

45. Bedek, G., Salaun, F., Martinkovska, Z., Devaux, E., and Dupont, D., *Evaluation of thermal and moisture management properties on knitted fabrics and comparison with a physiological model in warm conditions.* Appl Ergon, 2011. **42**(6): p. 792-800.

50. Fan, J.T. and Tsang, H.W.K., *Effect of clothing thermal properties on the thermal comfort sensation during active sports.* Textile Research Journal, 2008. **78**(2): p. 111-118.

51. Ho, C., Fan, J., Newton, E., and Au, R., *The effect of added fullness and ventilation holes in T-shirt design on thermal comfort.* Ergonomics, 2011. **54**(4): p. 403-10.

52. Troynikov, O. and Ashayeri, E., *Thermoregulatory evaluation of triathlon suits in regards to their physiological comfort properties.* Procedia Engineering, 2011. **13**: p. 357-362.

55. Roberts, B.C., Waller, T.M., and Caime, M.P., *Thermoregulatory response to base layer garments during treadmill exercise.* International Journal of Sports Science and Engineering, 2007. **1**(1): p. 29-38.

56. Wingo, J.E. and McMurray, R.G., *Cardiovascular and thermoregulatory responses to treadmill running while wearing shirts with different fabric composition.* Biology of Sport, 2007. **24**(2): p. 177-187.

57. Wickwire, J., Bishop, P.A., Green, J.M., Richardson, M.T., Lomax, R.G., Casaru, C., Curther-Smith, M., and Doss, B., *Physiological and comfort effects of commercial "wicking"*

clothing under a bulletproof vest. International Journal of Industrial Ergonomics, 2007. **37**(7): p. 643-651.

58. Laing, R.M., Sims, S.T., Wilson, C.A., Niven, B.E., and Cruthers, N.M., *Differences in wearer response to garments for outdoor activity.* Ergonomics, 2008. **51**(4): p. 492-510.

59. Brazaitis, M., Kamandulis, S., Skurvydas, A., and Daniuseviciute, L., *The effect of two kinds of T-shirts on physiological and psychological thermal responses during exercise and recovery.* Appl Ergon, 2010. **42**(1): p. 46-51.

60. Heus, R. and Kistemaker, L., *Thermal comfort of summer clothes for construction workers.* Environmental Ergonomics, 1998: p. 273-276.

61. Ha, M., Tokura, H., Yanai, Y., Moriyama, T., and Tsuchiya, N., *Combined effects of fabric air permeability and moisture absorption on clothing microclimate and subjective sensation during intermittent exercise at 27 degrees C.* Ergonomics, 1999. **42**(7): p. 964-79.

62. Stapleton, J.M., Hardcastle, S.G., and Kenny, G.P., *The influence of activewear worn under standard work coveralls on whole-body heat loss.* J Occup Environ Hyg, 2011. **8**(11): p. 652-61.

63. Kaplan, S. and Okur, A., *Thermal comfort performance of sports garments with objective and subjective measurements.* Indian Journal of Fibre & Textile Research, 2012. **37**(1): p. 46-54.

64. Noonan, B. and Stachenfeld, N., *The effects of undergarment composition worn beneath hockey protective equipment on high-intensity intermittent exercise.* J Strength Cond Res, 2012. **26**(9): p. 2309-16.

65. Sperlich, B., Born, D.P., Lefter, M.D., and Holmberg, H.C., *Exercising in a hot environment: which T-shirt to wear?* Wilderness Environ Med, 2013. **24**(3): p. 211-20.

69. Kicklighter, T.H., Edsall, J.R., and Martin, M., *Effect of Moisture-Wicking Garments on Temperature Regulation During Exercise.* International Journal of Athletic Therapy & Training, 2011. **16**(6): p. 9-13.

80. Park, S.J., Tokura, H., and Sobajima, M., *Effects of moisture absorption of clothing on pitching speed of amateur baseball players in hot environmental conditions.* Textile Research Journal, 2006. **76**(5): p. 383-387.

81. Gupta, D., *Functional clothing-Definition and classification.* Indian Journal of Fibre & Textile Research, 2011. **36**(4): p. 321-326.

82. Havenith, G., Fogarty, A., Bartlett, R., Smith, C.J., and Ventenat, V., *Male and female upper body sweat distribution during running measured with technical absorbents.* Eur J Appl Physiol, 2008. **104**(2): p. 245-55.

83. Smith, C.J. and Havenith, G., *Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia.* Eur J Appl Physiol, 2011. **111**(7): p. 1391-404.

84. Birnbaum, R.R. and Crockford, G.W., *Measurement of the clothing ventilation index.* Appl Ergon, 1978. **9**(4): p. 194-200.

85. Zhang, P., Gong, R.H., Yanai, Y., and Tokura, H., *Effects of clothing material on thermoregulatory responses.* Textile Research Journal, 2002. **72**(1): p. 83-89.

86. Zhang, X.H., Li, J., and Wang, Y.Y., *Effects of clothing ventilation openings on thermoregulatory responses during exercise.* Indian Journal of Fibre & Textile Research, 2012. **37**(2): p. 162-171.

87. Zhao, L., Hu, H., Shen, J.M., and Rong, H.R., *The use of a polytrimethylene terephthalate/polyester bi-component filament for the development of seamless garments.* Textile Research Journal, 2013. **83**(12): p. 1283-1296.

88. Robinson, S., Turrell, E.S., Belding, H.S., and Horvath, S.M., *Rapid Acclimatization to Work in Hot Climates.* 1943.

89. Borg, G.A., *Psychophysical bases of perceived exertion.* Med Sci Sports Exerc, 1982. **14**(5): p. 377-81.

92. Plante, A.M., Holcombe, B.V., and Stephens, L.G., *Fiber Hygroscopicity and Perceptions of Dampness .1. Subjective Trials.* Textile Research Journal, 1995. **65**(5): p. 293-298.

91. Livingstone, S.D., Reed, L.D., Nolan, R.W., and Cattroll, S.W., *Measurement of torso skin temperature under clothing.* Eur J Appl Physiol Occup Physiol, 1988. **57**(2): p. 225-9.

90. Davey, S.L., Barwood, M.J., and Tipton, M.J., *Thermal perceptions and skin temperatures during continuous and intermittent ventilation of the torso throughout and after exercise in the heat.* Eur J Appl Physiol, 2013. **113**(11): p. 2723-35.

CUMULATIVE REFERENCES

1. **Havenith, G.**, *Heat balance when wearing protective clothing.* Ann Occup Hyg, 1999. 43(5): p. 289-96.

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

3. **Goldman, R. and Kampmann, B.**, *Handbook on Clothing: Biomedical Effects of Military Clothing and Equipment Systems*. 2nd ed. 2007.

4. **Li, Y.**, *The science of clothing comfort.* Textile Progress, 2001. 31(1-2): p. 1-135.

5. **Pascoe, D.D., Shanley, L.A., and Smith, E.W.**, *Clothing and exercise. I: Biophysics of heat transfer between the individual, clothing and environment.* Sports Med, 1994. 18(1): p. 38-54.

6. **Munson, D. and Hayter, R.**, *Overview of Clothing as It Relates to Physiology of Human Comfort.* Ashrae Journal-American Society of Heating Refrigerating and Air-Conditioning Engineers, 1977. 19(12): p. 36-37.

7. **Binkley, H.M., Beckett, J., Casa, D.J., Kleiner, D.M., and Plummer, P.E.**, *National athletic trainers' association position statement: Exertional heat illnesses.* Journal of Athletic Training, 2002. 37(3): p. 329-343.

8. **Thein, L.A.**, *Environmental conditions affecting the athlete.* J Orthop Sports Phys Ther, 1995. 21(3): p. 158-71.

9. **Pascoe, D.D., Bellingar, T.A., and McCluskey, B.S.**, *Clothing and exercise. II. Influence of clothing during exercise/work in environmental extremes.* Sports Med, 1994. 18(2): p. 94-108.

10. **Nike Inc.**, *Fiscal Year 2013 Income Statement for the period ended May 31, 2013*. 2013.

11. **Under Armour Inc.**, *SEC Form 10-K for the Year Ended December 31, 2013*. 2014.

12. **Adidas AG**, *adidas Group Annual Report 2013*. 2013.

13. **Davis, J.K. and Bishop, P.A.**, *Impact of Clothing on Exercise in the Heat.* Sports Med, 2013.

14. **Bishop, P.A., Balilonis, G., Davis, J.K., and Zhang, Y.**, *Ergonomics and comfort in protective and sport clothing: A brief review.* Ergonomics, 2013. S2(005): p. 1-7.

15. **Brooks, G.A., Fahey, T.D., and Baldwin, K.M.**, *Excercise Physiology: Human Bioenergetics and Its Applications*. 4th ed. 2005, New York, NY: McGraw-Hill.

16. **Gavin, T.P.**, *Clothing and thermoregulation during exercise.* Sports Med, 2003. 33(13): p. 941-7.

17. **Powers, S.K. and Howley, E.T.**, *Exercise Physiology: Theory and Application to Fitness and Performance*. 8 ed. 2012, New York, NY: McGraw-Hill.

18. **Gleeson, M.**, *Temperature regulation during exercise.* International Journal of Sports Medicine, 1998. 19: p. S96-S99.

19. **Yard, E.E., Gilchrist, J., Haileyesus, T., Murphy, M., Collins, C., McIlvain, N., and Comstock, R.D.**, *Heat illness among high school athletes--United States, 2005-2009.* J Safety Res, 2010. 41(6): p. 471-4.

20. **Bross, M.H., Nash, B.T., Jr., and Carlton, F.B., Jr.**, *Heat emergencies.* Am Fam Physician, 1994. 50(2): p. 389-96, 398.

21. **McMorris, T., Swain, J., Smith, M., Corbett, J., Delves, S., Sale, C., Harris, R.C., and Potter, J.**, *Heat stress, plasma concentrations of adrenaline, noradrenaline, 5-hydroxytryptamine and cortisol, mood state and cognitive performance.* Int J Psychophysiol, 2006. 61(2): p. 204-15.

22. **Gonzalez-Alonso, J., Teller, C., Andersen, S.L., Jensen, F.B., Hyldig, T., and Nielsen, B.**, *Influence of body temperature on the development of fatigue during prolonged exercise in the heat.* Journal of Applied Physiology, 1999. 86(3): p. 1032-1039.

23. **Kwon, A., Kato, M., Kawamura, H., Yanai, Y., and Tokura, H.**, *Physiological significance of hydrophilic and hydrophobic textile materials during intermittent exercise in humans under the influence of warm ambient temperature with and without wind.* European Journal of Applied Physiology and Occupational Physiology, 1998. 78(6): p. 487-493.

24. **Prahsarn, C., Barker, R.L., and Gupta, B.S.**, *Moisture vapor transport behavior of polyester knit fabrics.* Textile Research Journal, 2005. 75(4): p. 346-351.

25. **Berglund, L.G. and Gonzalez, R.R.**, *Evaporation of Sweat from Sedentary Man in Humid Environments.* Journal of Applied Physiology, 1977. 42(5): p. 767-772.

26. **Nagata, H.**, *Evaporative heat loss and clothing.* J Hum Ergol (Tokyo), 1978. 7(2): p. 169-75.

27. **Li, Y.**, *Perceptions of temperature, moisture and comfort in clothing during environmental transients.* Ergonomics, 2005. 48(3): p. 234-48.

28. **Havenith, G.**, *The Interaction between clothing insulation and thermoregulation.* Exogenous Dermatology, 2002. 1(5): p. 221-230.

29. **Kadolph, S.J.**, *Textiles*. 10 ed. 2007, Upper Saddle River, NJ: Pearson Education, Inc.

30. **Gavin, T.P., Babington, J.P., Harms, C.A., Ardelt, M.E., Tanner, D.A., and Stager, J.M.**, *Clothing fabric does not affect thermoregulation during exercise in moderate heat.* Med Sci Sports Exerc, 2001. 33(12): p. 2124-30.

31. **Oglakcioglu, N. and Marmarali, A.**, *Thermal comfort properties of some knitted structures.* Fibres & Textiles in Eastern Europe, 2007. 15(5-6): p. 94-96.

32. **Hes, L. and Loghin, C.**, *Heat, moisture and air transfer properties of selected woven fabrics in wet state.* Journal of Fiber Bioengineering and Informatics, 2009. 2(3): p. 141-149.

33. **Das, B., Das, A., Kothari, V.K., Fangueiro, R., and de Araujo, M.**, *Moisture transmission through textiles part ii: Evaluation methods and mathematical modelling.* AUTEX Research Journal, 2007. 7(3): p. 194-216.

34. **Laing, R.M., Wilson, C.A., Gore, S.E., and Carr, D.J.**, *Determining the drying time of apparel fabrics.* Textile Research Journal, 2007. 77(8): p. 583-590.

35. **Li, Y.**, *Sensory comfort: Fabric transport properties and subjective responses during exercise under cool and hot environmental conditions.* Research Journal of Textile and Apparel, 1997: p. 84-93.

36. **Ueda, H. and Havenith, G.**, *The effect of fabric air permeability on clothing ventilation*, in *Environmental Ergonomics - The Ergonomics of Human Comfort, Health and Performance in the Thermal Environment*, Y. Tochihara and T. Ohnaka, Editors. 2005, Elsevier B. V. p. 343-346.

37. **Yoo, S. and Barker, R.L.**, *Moisture management properties of heat-resistant workwear fabrics - Effects of hydrophilic finishes and hygroscopic fiber blends.* Textile Research Journal, 2004. 74(11): p. 995-1000.

38. **Saricam, C. and Kalaoglu, F.**, *Investigation of the Wicking and Drying Behaviour of Polyester Woven Fabrics.* Fibres & Textiles in Eastern Europe, 2014. 22(3): p. 73-78.

39. **Zhuang, Q., Harlock, S.C., and Brook, D.B.**, *Transfer wicking mechanisms of knitted fabrics used as undergarments for outdoor activities.* Textile Research Journal, 2002. 72(8): p. 727-734.

40. **Simile, C.**, *Critical evaluation of wicking in performance fabrics*, in *School of Polymer, Textile, and Fiber Engineering*. 2004, Georgia Institute of Technology. p. 79.

41. **Yi, K.F.**, *Effect of heat and moisture transfer properties of t-shirts on comfort sensations*, in *Institute of Textiles and Clothing*. 2006, The Hong Kong Polytechnic University. p. 147.

42. **Dai, X.Q., Imamura, R., Liu, G.L., and Zhou, F.P.**, *Effect of moisture transport on microclimate under T-shirts.* Eur J Appl Physiol, 2008. 104(2): p. 337-40.

43. **Das, B., Das, A., Kothari, V., Fanguiero, R., and Araujo, M.D.**, *Moisture Flow through Blended Fabrics - Effect of Hydrophilicity.* Journal of Engineered Fibers and Fabrics, 2009. 4(4): p. 20-28.

44. **Fangueiro, R., Filgueiras, A., Soutinho, F., and Xie, M.D.**, *Wicking Behavior and Drying Capability of Functional Knitted Fabrics.* Textile Research Journal, 2010. 80(15): p. 1522-1530.

45. **Bedek, G., Salaun, F., Martinkovska, Z., Devaux, E., and Dupont, D.**, *Evaluation of thermal and moisture management properties on knitted fabrics and comparison with a physiological model in warm conditions.* Appl Ergon, 2011. 42(6): p. 792-800.

46. **Cubric, I.S., Skenderi, Z., Mihelic-Bogdanic, A., and Andrassy, M.**, *Experimental study of thermal resistance of knitted fabrics.* Experimental Thermal and Fluid Science, 2012. 38: p. 223-228.

47. **Yanilmaz, M. and Kalaoglu, F.**, *Investigation of wicking, wetting and drying properties of acrylic knitted fabrics.* Textile Research Journal, 2012. 82(8): p. 820-831.

48. **Bouskill, L.M., Havenith, G., Kuklane, K., Parsons, K.C., and Withey, W.R.**, *Relationship between clothing ventilation and thermal insulation.* Aihaj, 2002. 63(3): p. 262-268.

49. **Chen, Y.S., Fan, J.T., and Zhang, W.**, *Clothing thermal insulation during sweating.* Textile Research Journal, 2003. 73(2): p. 152-157.

50. **Fan, J.T. and Tsang, H.W.K.**, *Effect of clothing thermal properties on the thermal comfort sensation during active sports.* Textile Research Journal, 2008. 78(2): p. 111-118.

51. **Ho, C., Fan, J., Newton, E., and Au, R.**, *The effect of added fullness and ventilation holes in T-shirt design on thermal comfort.* Ergonomics, 2011. 54(4): p. 403-10.

52. **Troynikov, O. and Ashayeri, E.**, *Thermoregulatory evaluation of triathlon suits in regards to their physiological comfort properties.* Procedia Engineering, 2011. 13: p. 357-362.

53. **Havenith, G., Richards, M.G., Wang, X.X., Brode, P., Candas, V., den Hartog, E., Holmer, I., Kuklane, K., Meinander, H., and Nocker, W.**, *Apparent latent heat of evaporation from clothing: attenuation and "heat pipe" effects.* Journal of Applied Physiology, 2008. 104(1): p. 142-149.

54. **Ha, M., Yamashita, Y., and Tokura, H.**, *Effects of moisture absorption by clothing on thermal responses during intermittent exercise at 24 degrees C.* Eur J Appl Physiol Occup Physiol, 1995. 71(2-3): p. 266-71.

55. **Roberts, B.C., Waller, T.M., and Caime, M.P.**, *Thermoregulatory response to base layer garments during treadmill exercise.* International Journal of Sports Science and Engineering, 2007. 1(1): p. 29-38.

56. **Wingo, J.E. and McMurray, R.G.**, *Cardiovascular and thermoregulatory responses to treadmill running while wearing shirts with different fabric composition.* Biology of Sport, 2007. 24(2): p. 177-187.

57. **Wickwire, J., Bishop, P.A., Green, J.M., Richardson, M.T., Lomax, R.G., Casaru, C., Curther-Smith, M., and Doss, B.**, *Physiological and comfort effects of commercial "wicking" clothing under a bulletproof vest.* International Journal of Industrial Ergonomics, 2007. 37(7): p. 643-651.

58. **Laing, R.M., Sims, S.T., Wilson, C.A., Niven, B.E., and Cruthers, N.M.**, *Differences in wearer response to garments for outdoor activity.* Ergonomics, 2008. 51(4): p. 492-510.

59. **Brazaitis, M., Kamandulis, S., Skurvydas, A., and Daniuseviciute, L.**, *The effect of two kinds of T-shirts on physiological and psychological thermal responses during exercise and recovery.* Appl Ergon, 2010. 42(1): p. 46-51.

60. **Heus, R. and Kistemaker, L.**, *Thermal comfort of summer clothes for construction workers.* Environmental Ergonomics, 1998: p. 273-276.

61. **Ha, M., Tokura, H., Yanai, Y., Moriyama, T., and Tsuchiya, N.**, *Combined effects of fabric air permeability and moisture absorption on clothing microclimate and subjective sensation during intermittent exercise at 27 degrees C.* Ergonomics, 1999. 42(7): p. 964-79.

62. **Stapleton, J.M., Hardcastle, S.G., and Kenny, G.P.**, *The influence of activewear worn under standard work coveralls on whole-body heat loss.* J Occup Environ Hyg, 2011. 8(11): p. 652-61.

63. **Kaplan, S. and Okur, A.**, *Thermal comfort performance of sports garments with objective and subjective measurements.* Indian Journal of Fibre & Textile Research, 2012. 37(1): p. 46-54.

64. **Noonan, B. and Stachenfeld, N.**, *The effects of undergarment composition worn beneath hockey protective equipment on high-intensity intermittent exercise.* J Strength Cond Res, 2012. 26(9): p. 2309-16.

65. **Sperlich, B., Born, D.P., Lefter, M.D., and Holmberg, H.C.**, *Exercising in a hot environment: which T-shirt to wear?* Wilderness Environ Med, 2013. 24(3): p. 211-20.

66. **Brownlie, L., Mekjavic, I., and Banister, E.**, *Thermoregulation in athletic racing apparel.* Ann Physiol Anthropol, 1987. 6(3): p. 145-55.

67. **De Sousa, J., Cheatham, C., and Wittbrodt, M.**, *The effects of a moisture-wicking fabric shirt on the physiological and perceptual responses during acute exercise in the heat.* Appl Ergon, 2014. 45(6): p. 1447-53.

68. **Gonzales, B.R., Hagin, V., Guillot, R., Placet, V., and Groslambert, A.**, *Effects of polyester jerseys on psycho-physiological responses during exercise in a hot and moist environment.* J Strength Cond Res, 2011. 25(12): p. 3432-8.

69. **Kicklighter, T.H., Edsall, J.R., and Martin, M.**, *Effect of Moisture-Wicking Garments on Temperature Regulation During Exercise.* International Journal of Athletic Therapy & Training, 2011. 16(6): p. 9-13.

70. **Holme, I.**, *Innovative technologies for high performance textiles.* Coloration Technology, 2007. 123(2): p. 59-73.

71. **Havenith, G., Heus, R., and Lotens, W.A.**, *Clothing Ventilation, Vapor Resistance and Permeability Index - Changes Due to Posture, Movement and Wind.* Ergonomics, 1990. 33(8): p. 989-1005.

72. **Chi, T. and Kilduff, P.**, *Understanding consumer perceived value of casual sportswear: An empirical study.* Journal of Retailing and Consumer Services, 2011. 18: p. 422-429.

73. **Hes, L. and Dolezal, I.**, *New method and equipment for measuring thermal properties of textiles.* Journal of the Textile Machinery Society of Japan, 1989. 42(8): p. 124-128.

74. **American Society for Testing and Materials**, *ASTM D737, Standard Test Method for Air Permeability of Textile Fabrics*. 2012, ASTM International: West Conshohocken, PA.

75. **American Society for Testing and Materials**, *ASTM E96, Standard Test Methods for Water Vapor Transmission of Materials*. 2013, ASTM International: West Conshohocken, PA.

76. **American Association of Textile Chemists and Colorists**, *AATCC TM 197, Vertical Wicking of Textiles*. 2013, American Association of Textile Chemists and Colorists: Research Triangle Park, NC.

77. **Yoon, H.N. and Buckley, A.**, *Improved Comfort Polyester .1. Transport-Properties and Thermal Comfort of Polyester Cotton Blend Fabrics.* Textile Research Journal, 1984. 54(5): p. 289-298.

78. **Huang, J.H.**, *Sweating guarded hot plate test method.* Polymer Testing, 2006. 25(5): p. 709-716.

79. **Harnett, P.R. and Mehta, P.N.**, *A Survey and Comparison of Laboratory Test Methods for Measuring Wicking.* Textile Research Journal, 1984. 54(7): p. 471-478.

80. **Park, S.J., Tokura, H., and Sobajima, M.**, *Effects of moisture absorption of clothing on pitching speed of amateur baseball players in hot environmental conditions.* Textile Research Journal, 2006. 76(5): p. 383-387.

81. **Gupta, D.**, *Functional clothing-Definition and classification.* Indian Journal of Fibre & Textile Research, 2011. 36(4): p. 321-326.

82. **Havenith, G., Fogarty, A., Bartlett, R., Smith, C.J., and Ventenat, V.**, *Male and female upper body sweat distribution during running measured with technical absorbents.* Eur J Appl Physiol, 2008. 104(2): p. 245-55.

83. **Smith, C.J. and Havenith, G.**, *Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia.* Eur J Appl Physiol, 2011. 111(7): p. 1391-404.

84. **Birnbaum, R.R. and Crockford, G.W.**, *Measurement of the clothing ventilation index.* Appl Ergon, 1978. 9(4): p. 194-200.

85. **Zhang, P., Gong, R.H., Yanai, Y., and Tokura, H.**, *Effects of clothing material on thermoregulatory responses.* Textile Research Journal, 2002. 72(1): p. 83-89.

86. **Zhang, X.H., Li, J., and Wang, Y.Y.**, *Effects of clothing ventilation openings on thermoregulatory responses during exercise.* Indian Journal of Fibre & Textile Research, 2012. 37(2): p. 162-171.

87. **Zhao, L., Hu, H., Shen, J.M., and Rong, H.R.**, *The use of a polytrimethylene terephthalate/polyester bi-component filament for the development of seamless garments.* Textile Research Journal, 2013. 83(12): p. 1283-1296.

88. **Robinson, S., Turrell, E.S., Belding, H.S., and Horvath, S.M.**, *Rapid Acclimatization to Work in Hot Climates.* 1943.

89. **Borg, G.A.**, *Psychophysical bases of perceived exertion.* Med Sci Sports Exerc, 1982. 14(5): p. 377-81.

90. **Davey, S.L., Barwood, M.J., and Tipton, M.J.**, *Thermal perceptions and skin temperatures during continuous and intermittent ventilation of the torso throughout and after exercise in the heat.* Eur J Appl Physiol, 2013. 113(11): p. 2723-35.

91. **Livingstone, S.D., Reed, L.D., Nolan, R.W., and Cattroll, S.W.**, *Measurement of torso skin temperature under clothing.* Eur J Appl Physiol Occup Physiol, 1988. 57(2): p. 225-9.

92. **Plante, A.M., Holcombe, B.V., and Stephens, L.G.**, *Fiber Hygroscopicity and Perceptions of Dampness .1. Subjective Trials.* Textile Research Journal, 1995. 65(5): p. 293-298.

APPENDIX A

Auburn University
Auburn University, Alabama 36849-5323

School of Kinesiology
301 Wire Road
Thermoregulation Lab (Room 260)

Telephone: (334) 844-4483
Fax: (334) 844-1467
Thermal Lab: (334) 844-1619

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

INFORMED CONSENT

for a Research Study entitled

"Fabric Analysis, Design Implementation, and Physiological and Subjective Testing of a Novel Sportswear Garment"

You are invited to participate in a research study to determine the efficacy of a newly constructed sportswear shirt on minimizing heat stress and maximizing comfort while exercising in a hot environment. The study is being conducted by Khalil Lee, doctoral candidate, in the Auburn University School of Kinesiology. You were selected as a possible participant because you meet the study inclusion criteria (PAR-Q medical screening, VO2 minimum of 35 ml/kg/min) and are 19-35 years old.

What will be involved if you participate? If you decide to participate in this research study, you will be asked to complete a VO2max aerobic fitness test, three 90 minute acclimation trials, one protocol familiarization trial, and three 90 minute test trials. During these acclimation and test trials, you will be cycling in a hot, dry environment. The trials will involve the measurement of physiological (heart rate, core temperature, skin temperature, sweat rate) and subjective (perceived exertion, thermal sensation, wetness sensation, thermal comfort) responses. Your total time commitment will be approximately 11 hours.

Are there any risks or discomforts? Due to the nature of the trials (exercise in a hot environment), there is risk of physical harm (heat related illness; muscle strains) and, in rare cases, death. The American College of Sports Medicine estimates the risk of death at 0.5 per 10,000 individuals (ACSM Guidelines). There is also a risk of breach of confidentiality, as identifiable data will be accessed.

What precautions are taken to minimize any risks? Heat related illness will be minimized by monitoring hydration status and by constantly monitoring heart rate and core temperature during each trial. Acclimation trials will allow the researchers and participants to determine the potential for the successful completion of the test trials under the set environmental conditions. Finally, the principle investigator and research personnel have considerable experience with thermal testing. All participants will be healthy as defined by their completion of the PAR-Q medical questionnaire. Participant ages are limited to 19-35 years. VO2max testing and the inclusion criteria of 35 ml/kg/min assures the participant has a moderate fitness levels prior to engaging in the heat trials. Participants will be under the constant supervision of the principle investigator and other research personnel during trials. If during the trials, your core temperature gets to 39.5°C (103°F), your heart rate is within 10 beats of max, or you experience volitional fatigue or do not want to continue, trials will be immediately terminated.

Are there any benefits to yourself or others? If you participate in this study, you can expect to receive your personal test results (VO2-HR workload determinations, sweat rate, body composition) pertaining to your fitness level and heat related responses.

Will you receive compensation for participating? To thank you for your time, you will be allowed to keep the shirt worn for each of the three test trials completed (three shirts total).

If you change your mind about participating, you can withdraw at any time during the study. Your participation is completely voluntary. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University or the School of Kinesiolgy.

Your privacy will be protected. Any information obtained in connection with this study will remain confidential. Information obtained through your participation will be included in the principal investigator’s dissertation and may be published in a professional journal, presented at a professional meeting.

If you have any questions about this study, *please ask them now* or contact Khalil Lee at (334)-728-0250 or at kal0017@auburn.edu

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Research Compliance or the Institutional Review Board by phone (334)-844-5966 or e-mail at IRBadmin@auburn.edu or IRBchair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

Participant's signature	Printed Name	Date
______________________________	____________________________	__________
Investigator obtaining consent	Printed Name	Date
______________________________	____________________________	__________
Co-Investigator	Printed Name	Date
_______________________________	____________________________	___________

APPENDIX B

PAR Q Medical Questionnaire*

Please read each question carefully and answer honestly. If you do not understand the question, please ask the investigator for clarification. Check the appropriate answer.

No Yes

_____ _____ 1. Are you under 19 or over the age of 60?

_____ _____ 2. Do you presently smoke or have been a regular smoker?

_____ _____ 3. Has your doctor ever said you have heart trouble?

_____ _____ 4. Do you have a family history of early cardiovascular death before the age of 50?

_____ _____ 5. Have you ever had a heart murmur, rheumatic fever or respiratory problems?

_____ _____ 6. Have you ever been told that you have a fast resting heart rate?

_____ _____ 7. Have you ever been told by your doctor or nurse that your blood pressure is too high?

_____ _____ 8. Have you ever been told that your cholesterol is too high?

_____ _____ 9. Have you been told that you have a kidney disorder?

_____ _____ 10. Have you been told that you have diabetes or that your blood sugar is too high?

_____ _____ 11. Have you been told that your electrocardiogram (EKG), 12 lead EKG or stress test is not normal?

_____ _____ 12. Has your doctor ever told you that you have a muscle, bone, or joint problem such as arthritis that has been aggravated by exercise, or might be made worse by exercise?

_____ _____ 13. Have you felt faint, dizzy, or passed out during or after exercise?

_____ ______ 14. Do you have a family history related to being faint, dizzy, or passing during or after exercise?

_____ _____ 15. Have you ever felt pain, pressure, heaviness, or tightness in the chest, neck, shoulders, or jaws as a result of exercise?

Initials _________

PAR Q Medical Questionnaire *

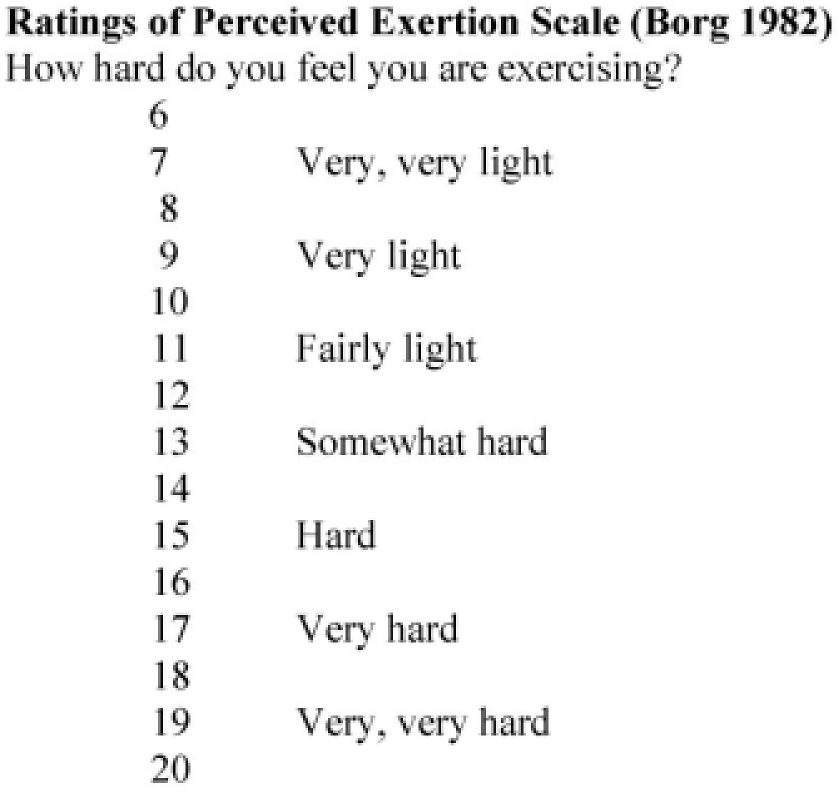
Page 2 of 2

No	Yes	
_____	_____	16. Have you been hospitalized in the past year?
_____	_____	17. Have you ever had problems related to heat or cold stress or experienced some temperature regulation problem?
_____	_____	18. Have you ever had problems with heat rashes?
_____	_____	19. Are you taking prescription medicine? If so, what? ____ ____
_____	_____	20. Do you have any reason to believe that your participation in this investigative effort may put your health or well being at risk? If so, please state reason. ___________ ____

Signature of subject ____________________________ Date ___________________

*Adapted from British Columbia Department of Health and Michigan Heart Association

APPENDIX C



Ratings of Perceived Exertion Scale (Borg 1982)

How hard do you feel you are exercising?

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

APPENDIX D

Perceptual Responses

Thermal Sensation
Rate how the temperature of your body feels by placing a mark on the line below.

Neutral Very Hot

Thermal Comfort
Rate how comfortable your body feels in the garment by placing a mark on the line below.

Comfortable Extremely Uncomfortable

Wetness Sensation
Rate how wet your body feels in the garment by placing a mark on the line below.

Dry Very Wet

Comments: