Engineering Comfort for Micro-resolution Mosquito Bite Blocking Textiles

by

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Abstract

Over a million people die yearly from diseases spread by biting insects, especially mosquitos. Pesticides are currently used to control harmful insect populations although there are often negative side effects from pesticides. In addition, there is a long tradition of using bed nets to protect against mosquito-borne diseases. Bed nets are still widely used today. However, natural selection and nature have resulted in some mosquitoes adapting to bed nets and becoming resistant to insecticides. Humans can also protect themselves from bites via thick clothing. However, thin comfortable clothing that also blocks mosquito bites is uncommon. This study aims to examine many known knit structures and their variable parameters that can be used to create a knit with micro-resolution mosquito bite blocking and high comfortability. Prior researchers found that a single knit structure, interlock, after washing, can block mosquito bites regardless of the fiber used for the yarns. I tested a variety of knit structures including the interlock knit with various fiber compositions toward the task of engineering more comfortable mosquito blocking clothing. Various tests were conducted to evaluate a given textile's comfort, including air permeability, water wicking, temperature difference, and a 9-factor perceived hand-feel comfort test. This thesis aims to quantify comfort and engineer specific properties that contribute to comfort. Major conclusions drawn from this thesis are that: i) Using Spandex/Nylon blends to construct mosquito bite blocking textiles yields most comfortable garments; ii) The structures Interlock, Half-Cardigan, and Jersey Skip were able to maintain a low body temperature no matter what yarn was being used, in comparison to the Under Armour control; iii) The combination of Spandex/Nylon creates a synergic effect improving the water wicking ability of a textile; iv) The air permeability might be a good predictor of mosquito bite

blocking capability, textiles that are too permeable and are unlikely to block; Half-Cardigan, Single Jersey, and Jersey-Skip knits can block mosquito bites with Spandex additions.

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List of Abbreviations

AU	Auburn University
CDC	Center for Disease Control
EPA	Environmental Protection Agency
ITNs	Insecticide-treated Nets
ITMs	Insecticide-treated Materials
PE	Polyethylene
RH	Relative Humidity

Chapter 1: Introduction

1.1 Mosquitoes

Life Cycle

Mosquitos are hematophagous (blood sucking) flies that spread disease amongst humans. Mosquitos often reproduce in stagnant freshwater (Oladepo et al., 2010). Stagnant is a term for nonflowing water, such as ponds and puddles (Oladepo et al., 2010). After fertilization, eggs are oviposited in water or near water by the female mosquitos. *Culex* eggs stick to each other to form what is called a raft, while other species of mosquitos lay individual eggs (Hinton, 1968). The eggs then hatch into larvae. Although larvae are found in water, they do not have gills. Their respiratory systems functions of breathing air. Because of this, larvae tend to float on the surface of water to make this respiratory action easier (Crans et al., 2004). Larvae will move to the bottom if they sense shadows (CDC, 2020). The Larvae stage lasts ~10 days depending on temperature. After, the larval instar molts are the pupal stage (CDC, 2020). Like larvae, the pupae still require oxygen but no longer feed. Pupation takes a few days to transform into the final adult stage (Magori et al., 2009). Adults fly with a set of wings, hence the order Diptera, which means (two wings). Male mosquitos feed from nectar from flowers (Barredo et al., 2020). Female mosquitos feed from the blood of animals and humans (Barredo et al., 2020). The blood is used to form eggs and restarts the life cycle (Roubaud, 1929). Male mosquitos typically don’t live long after a week, but females can live up to 1-2 months (Kauffman et al., 2017).

Consequences of Mosquito Feeding

The feeding of blood by some female mosquitoes can lead to the spread of dangerous vector-borne diseases. Prevalent diseases include malaria, Dengue, West Nile, Yellow fever, Zika, chikungunya, and lymphatic filariasis (CDC, 2019). Over one million human deaths each year are caused by these diseases (WHO, 2020). As a result of this high mortality rate, mosquitoes are the world's deadliest animals (AMCA, n.d.). *Anopheles* species spread malaria; one vector-borne disease with arguably the greatest impact on human health. The pathology is caused by infection of blood and liver cells (erythrocytes and hepatocytes) by the *Plasmodium* parasite. Malaria alone was responsible for 627,000 deaths in 2020, according to the World Health Organization (WHO, 2020). A high fever and chills are common symptoms similar to the flu.

Mosquitos also transmit viruses. Yellow fever, a flavivirus, is transmitted by *Aedes aegypti.* The *Aedes* mosquitos (commonly *Aedes aegpyti* and *albopictus*) transmit other flaviviruses like dengue and zika *(*Thangamani et al., 2016). Yellow Fever is deadly, although there is an effective vaccine. Thus, death from yellow fever is less common. In addition, many people infected with yellow fever are asymptomatic and do not show signs of illness (Guarner et al., 2019). However, you may experience symptoms such as nausea, fever, headaches, yellow eyes, or even more serious conditions such as heart disease, liver disease, and kidney disease (Guarner et al., 2019).

Dengue is an extremely serious disease, also known as “break bone fever”. Initial infections with Dengue can incapacitate a human for 2-3 weeks. Secondary infections of Dengue with a different serotype can induce antibody dependent enhancement (ADE) (Cummings et al., 2005). ADE causes Dengue shock syndrome which can also be deadly. Thus, *Aedes aegypti* is amongst the most dangerous mosquito species (Carvalho et al., 2017).

Mosquitos of the genus *Culex* can transmit a parasitic nematode to the lymph nodes and the body's lymph vessels (Chandy et al., 2011). Elephantiasis is another term for this condition.

When one contracts an infection with filarial parasites, your skin is likely to become swollen and thickened with swelling (Mortimer, 1989). This parasitic disease is most likely to be contracted by children during childhood when they are most vulnerable to it. There are 36 million cases of elephantiasis that occur each year (Hotez et al., 2009). It’s an extremely important disease. In summary, mosquitos of various species spread all kinds of pathogens including single celled eukaryotic protists, viruses, and nematodes. Efforts to prevent the transmission of these diseases are desperately needed.

1.2 Mosquito Management

Insecticides

For first world countries, it is has become routine to prevent the vector-borne diseases mentioned above by following a few simple practices. The most common method of controlling insects is using insecticides. Insecticides are an extremely important tool in the fight against vector borne disease. In the past, some insecticides like DDT have gone out of favor for negative environmental side effects (Van den Berg, 2009). For the control of mosquitoes, pyrethroids are the most used insecticide. For personal protection, insecticides can be impregnated into textiles (Faulde et al., 2006). This is an effective treatment used by the military on its own textiles. However, often humans do not like the idea of wearing clothing laced with chemical insecticides. Thus, a mechanical means of blocking mosquito bites with comfortable textiles without insecticides makes sense and could prove a valuable product.

Textiles preventing vector-borne diseases have a long history. In the fight against arthropod-borne diseases, such as malaria, bed nets treated with insecticides have played an important role. In 1983, insecticide-treated nets (ITNs) were developed and used in Burkina Faso (Robert, 2020). It is common for ITNs to be used in African countries to combat malaria transmission and deaths (Nyarango et al., 2020). Pyrroles and pyrethroids are the two insecticide classes approved by the Centers for Disease Control for ITNs (CDC, 2019). However, the EPA has only approved pyrethroid-based insecticides for application to bed nets (Kitchen, 2009). Pyrethroids come from flowers and are widely used domestically and commercially (Bradberry. 2005). The insect's nervous systems are the primary target of insecticides (Sällenbergfait, 2015). Pyrethroid insecticides are highly effective against insects. For example, the military uses insecticide-treated clothing to prevent the transmission of deadly diseases (Croft et al., 2006). However, no studies have been conducted to determine their effects on humans. Studies have shown that prolonged exposure to pyrethroids may pose serious health risks to people and ecosystems (Jabeen, 2015). Pyrethroids also are quite stable and do not degrade easily (Jabeen, 2015). One problem with impregnated textiles is that the insecticides wash out during standard laundering. This is problematic in two ways. First, it decreases the effectiveness of the insect prevention and secondarily it might cause runoff insecticide contamination in drain water.

Vector Control

By focusing on the prevention of selected neglected tropical diseases (NTDs) whose transmission cycle relies on vectors or intermediate hosts, vector control is an effective strategy (WHO, 2021). A good way to control mosquitos at home is to remove standing water. This involves covering water storage containers, filling in holes where water cannot sit, and emptying and scrubbing any items outside that can retain water on a weekly basis (CDC, 2020). Adult mosquitoes can also be killed in areas where they rest by using an outdoor adulticide (CDC, 2020). Individuals can spray under patio furniture, under the carport, or in the garage if the area is humid and dark to minimize the population of mosquitos (CDC, 2020).

Professionals are also available to control vectors. By coordinating community-wide cleanup drives, humans can remove standing water and dispose of any containers that can be used to store water (CDC, 2020). By altering habitats, such as regarding drainage ditches, water can drain quickly and avoid accumulating as standing water (CDC, 2020). Proper management of drainage systems, such as culverts, storm drains, or ditches on the sides of roads can limit mosquito populations and disease transmission (CDC, 2020). C

Natural Remedies

While natural remedies are often considered non-scientific. There can be truth behind anecdotal treatments. For example, Tu Youyou, shared the Nobel prize in 2015 for the identification of the anti-malarial Artemisinin which was described in early traditional Chinese medicine (Liu et al., 2016). It is believed that there are natural remedies that can cure or prevent viral infections. The use of traditional medicinal plants and herbs for treating viral infections in humans and animals was reported in various studies to possess antiviral and anti-dengue properties (Lal Choudhary, 2022). In order to treat a variety of diseases, including dengue-related problems, extracts from various parts of plants, such as leaves, fruits, bark, and stems, are used (Santos et al., 2012). Phytochemical compositions of plant species have been shown to exhibit various actions against mosquito vectors and pathogens. Some examples describe are larvicidal, ovicidal, virucidal, and mosquitocidal activities; some plant compounds are also repellant to mosquitoes (Lal Choudhary, 2022). Immunity to viral diseases such as Dengue was increased by using natural remedies and plant-based products (Zamora-Mendoza et al., 2022).

Insecticide-Treated Textiles

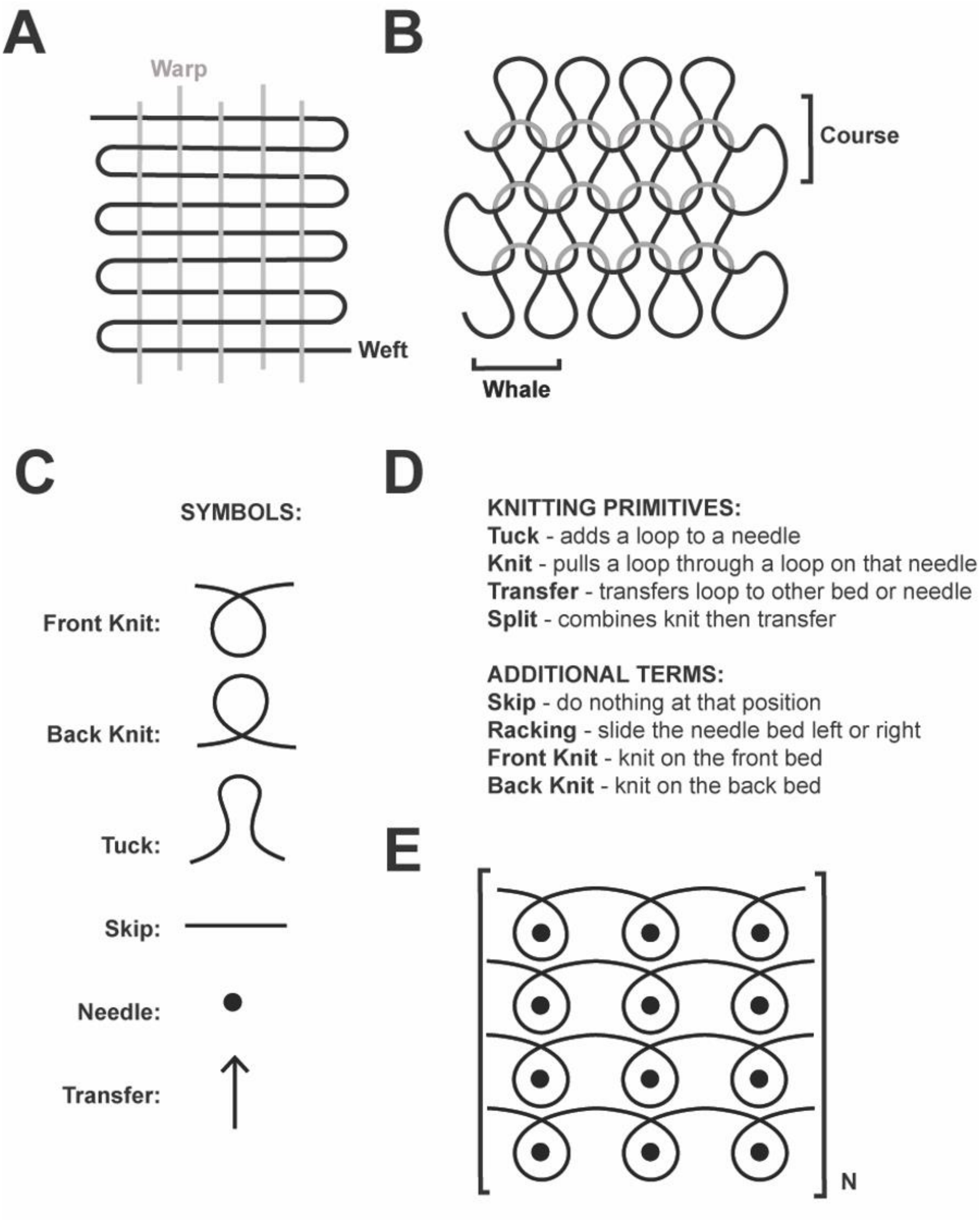
Insects, mosquitoes, and other arthropods can be prevented from entering through textiles (Anuar, 2016). In the present day, textile products designed to provide protection against mosquitoes are extensively used by consumers (Anuar, 2016). A spray of pyrethroid gathering, such as permethrin, can be used as a fast-acting aerosol on clothing to prevent mosquitoes from arriving or spreading (Anuar, 2016). These mixes are not capable of completely repelling mosquitoes and allowing them to reach the fabric. Upon contact they are aggravated or killed before they can feed (Anuar, 2016). It is more desirable to apply anti-agents to clothes and fabrics rather than to the skin since it reduces the likelihood of hypersensitivity reactions (Anuar, 2016). Compared to applying chemicals directly to the skin, this application is one step up; however, the chemicals will be washed away after a certain number of cycles and will have to be reapplied. Insecticide chemicals are still dangerous chemicals and can cause health problems if inhaled or worn.

1.3 Textiles

Methods of Textile Manufacturing

Fabrics for garments are manufactured in three main methods: nonwovens, wovens, and knits Fig 1. The two most popular methods of creating clothing are knitting and weaving (Adanur, 1995). In knitting, loops are interlaced either in the warp or weft direction (Anbumani, 2007). Warp yarns lie parallel to the fabric edge, and weft yarns lie perpendicular to the fabric edge (Crane eta l., 2017). Knitted fabrics can stretch far more than woven fabrics (Fan, 2020).

Woven fabrics are not very elastic. This is because they can only stretch in one direction, unlike knitted fabrics, which can stretch in any direction (Anbumani, 2007). Knitting consists of two processes: weft (or filling) knitting and warp knitting (Anbumani, 2007). Both methods involve the formation of loops to create malleable textiles; however, their approaches differ significantly. In warp knitting, loops are constructed into columns Fig 1 (Mohamed, 1990).



KNITTING PRIMITIVES:
Tuck - adds a loop to a needle
Knit - pulls a loop through a loop on that needle
Transfer - transfers loop to other bed or needle
Split - combines knit then transfer

ADDITIONAL TERMS:
Skip - do nothing at that position
Racking - slide the needle bed left or right
Front Knit - knit on the front bed
Back Knit - knit on the back bed

Figure 1 Knit Structure. (A) Process of weave manufacturing uses multiple independent warp and weft fibers. **(B)** Process of knit manufacturing uses single fibers and draws loops through loops to form courses (rows) and whales (columns) which form a sheet. **(C)** Symbology used in knit diagrams. Front knits are pulling a loop onto the front needle bed and a back knit onto the back needle bed. Tuck draws a loop onto a needle but doesn't pull it through a prior loop. Skip passes a needle. Dots represent needles and arrows represent transfers of loops from back to front needle bed or visa versa. **(D)** Primitive movements of knitting machines are described. **(E)** Represents an example of a knit diagram demonstrating a repeating pattern of front knits.

Knitted fabrics offer several advantages over woven fabrics, including the fact that their natural elasticity makes them more comfortable and better suited to conform to the human body. In addition, due to the natural open structure of loops, they have a higher shrinkage capability, higher moisture absorption, and higher air permeability, and are more resistant to creasing (Anbumani, 2007).

Both single-use (or disposable) and durable clothing are manufactured using nonwovens. A few major nonwoven markets include protective clothing, garment linings, interlinings, waddings, shoe linings, and synthetic leather fabrics. (Mao, 2015). As a result of their relatively low cost of production, versatility in incorporating multiple mechanical properties, disposability, and low lint, nonwoven fabrics have traditionally been used in medical applications (Ajmeri, 2010). In addition, the fact that they minimize cross-infection and maintain high levels of hygiene has enabled them to gain traction in the growing field of healthcare and hygiene (Ajmeri, 2010). However non-woven garments are not considered comfortable and are not the typical choice of day-to-day wear for humans.

Yarn Characteristics

Fibers are the lowest layer of textile structure. Fibers come together to form yarns. the fiber content gives yarns different characteristics. Polyester is a standard synthetic yarn used because of its low price. Polyester is strong, resistant to stretching and shrinking, resistant to most chemicals, quick-drying, crisp and resilient, wrinkle resistant, mildew resistant, abrasion resistant, retains heat-set pleats and creases, and quickly washed (Kiron, 2022). Spandex is a synthetic polymer (Kiron, 2021). The primary use for spandex fibers is fabric (Kiron, 2021). They can be stretched repeatedly and return almost precisely to their original size and shape (Kiron, 2021). Characteristics of spandex are low luster, stretchy, burning slowly, low conductivity, and low moisture removal (Kiron, 2021). Nylon is also a typical yarn that is used for athletic clothes. Nylon properties include elasticity, dries quickly, is very strong, and does not absorb water (Truents, 2018). These three yarns were accessible to our lab and were used in perfecting a comfortable textile.

External Previous Studies on Mosquito Blocking Textiles

It has been demonstrated that a new form of bed net can effectively kill mosquitoes without the need for insecticides. Students at NC State University have recently developed what they call an attract-trap-kill bed net (Mouhamadou, 2020). Using a cone-shaped knitting structure, this bed net traps and kills mosquitoes at a 4.3-fold rate superior to Permanent 2.0, the most used bed net in Africa (Mouhamadou, 2020). Mosquitos cannot escape the knit, so they die. Furthermore, when used at the community level, the product significantly improved control rates against insecticide-resistant Anopheles species (Mouhamadou, 2020).

The development of insecticide-free nets for agricultural use has also been studied, but their application to garments is a new and underdeveloped area that needs further research. There are many garments that are treated with insecticide so that they can prevent insect bites as well as the spread of arthropod-borne diseases. As a result of the occurrence of insecticide resistance and constant exposure to pyrethroids, there are, however, health concerns associated with these factors (Luan, 2021). There are a lot of difficulties involved in developing textiles that are insecticide-free. In mechanical terms, it is challenging to block a flexible needle with a diameter of 25 μm.

Recent research conducted at NC State University has resulted in the development of garments that remove the need for insecticides and are capable of physically preventing mosquito bites (Luan, 2021). To achieve this goal, the researchers used an ultrafine synthetic knit weighted at 96 grams per square meter, consisting of 80 percent polyamide of a denier count of 20 along with 20 percent elastane of a denier count of 20 (Luan, 2021). In the textile industry, denier count refers to the weight in grams per 9000 meters of fabric. Human hair is estimated to have a denier of around 20, whereas microfibers have a denier of less than 1, usually around 0.9 (SF, 2020). This garment consists of a jersey knit (front-facing loops on each needle) with pores ranging from 20 μm to 28 μm, providing adequate ventilation (Luan, 2021). It is necessary to develop a breathable garment during the summer months when mosquitoes are most active. Breathability can be measured in a few ways such as air permeability, water vapor permeability, water vapor resistance (Adámek, 2021).

According to NC State University's most recent study, a volunteer wore the garments for 10 minutes in a walk-in cage with 200 mosquitoes, and the volunteer found that the shirt prevented bites by 100 percent (Luan, 2021). A volunteer was bitten on the back and shoulders by 200 mosquitoes in the first trial testing the base layer. In order to reach blocking of 100 percent, the researchers doubled the material layer around the shoulders to prevent stretching and deforming of the fabric (Luan, 2021). A comfort test was also conducted along with a moisture and heat release test to determine how well the clothing trapped heat and released moisture (Luan, 2021). As a result of the fabric being added, trapped heat and moisture scores will increase. This research demonstrates that textiles can be engineered to block mosquito bites, but how to precisely engineer blocking in a scalable manufacturing process remains to be determined. Comfort of blocking knits is also an aspect that needs to be more studied. It is the lab's goal to create a shirt that is comfortable in a single layer and does not trap heat or moisture. The next chapter details efforts to quantify and engineer comfort of mosquito bite blocking textiles.

Previous Lab Studies on Mosquito Blocking Textiles

The lab performed a preliminary screening of common clothing to identify any potential blocking textiles. The experiment involved placing an arm with a sleeve in a cage containing 20 female mosquitoes for 15 minutes. To quantify bites received, we performed a bite count (Holt et al., 2023). It was found that five of the common weaves tested did not block, but one knit did. A few modern clothing items, including Under Armour compression heat gear, Nike socks, and two garments that advertise insect protection, including Rynoskin and a protective horse mesh, did not prevent bites (Holt et al., 2023). Based on a microscopy examination, it was discovered that these textiles contained numerous openings through which mosquitoes were capable of probing. Wearing non-blocking clothing also reduces human perception of mosquito landing events (Fig 2F) thus humans might actually receive more bites if they wear non-blocking textiles because naked skin would allow them to perceive and swat the mosquito. Due to the ease with which mosquitoes can penetrate clothes, we quantified where most common garments cling to the skin (Fig 2E). Long-sleeved shirts are not much more protective than short-sleeved shirts because both adhere to the skin in large areas of the upper back and shoulders, as well as on parts of the arms (Fig 2F). It was found that knits were capable of blocking mosquito bites with varying degrees of effectiveness following initial experiments (Holt et al., 2023). The purpose of this study was to determine what features and parameters were responsible for the blocking effect. In order to determine the best-knit geometries, we screened eight distinct knit geometries (Fig 3). During a standard wash-dry cycle, we observed that polyester knits shrank because of the heat. A non-blocker knit was converted into a blocker after post-knit heat treatment (Fig 3I-J). We then heat treated all knit garments by means of a wash and dry cycle (Holt et al., 2023). In the eight knits screened, only one was blocked, which we refer to as the interlock knit. A unique feature of the interlock knit is the placement of interlocking loops on top of each other (Fig 3D). We sought to identify treatments and parameters that would increase the blocking properties of a non-blocking knit (Holt et al., 2023). Three additional parameters were discovered that can enhance mosquito bite blocking. With an increase in thread diameter, a single-jersey knit became a blocking knit; with an increase in spandex, a jersey-skip knit became a blocking knit (Holt et al., 2023). Finally, decreasing stitch length enhanced blocking of the interlock knit (Holt et al., 2023). On blocking knits mosquitos probe more, although their total probing time was less because they fly away if they are unable to acquire bloodmeals (Holt et al., 2023). As part of our testing, blocking knits were tested against both *Aedes aegypti* and *Psorophora howardii*. In colloquial terms, *Psorophora* is known as a "giant mosquito" due to the size of its proboscis, which is much larger than the proboscis of *Aedes* (Holt et al., 2023). No textile tested was thicker than a mosquito proboscis. The results indicate that our knits are effective in blocking mosquitoes of more than one species (Holt et al., 2023). To generate the blocking effect, it is often necessary to develop unique recipes that include different fiber contents, diameters, and knit geometries to optimize them for blocking.

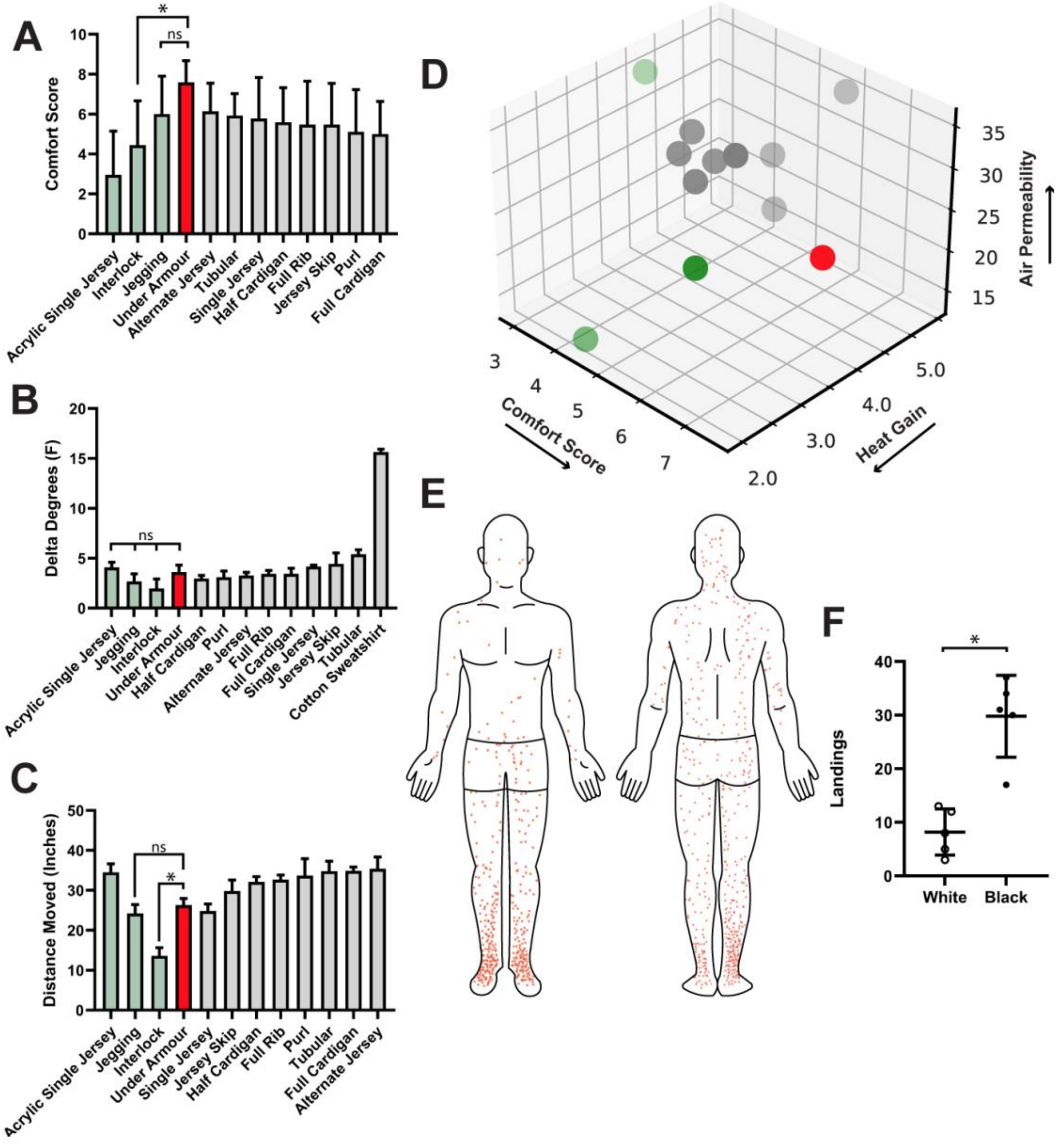


Figure 2 Collection of Scores Expressed Together. Engineering comfort of bite blocking textiles. **(A)** Mean comfort scores of combined 9- factor feel tests on textiles. A higher score

indicates higher comfort. Red is a comfortable *Under Armour* control and green are blocking textiles. **(B)** Average heat gained on skin beneath textile sleeves. A lower score indicates higher comfort (less heat gained). **(C)** Average air permeability of corresponding textile sleeves. Y-axis is distance of salt particles moved by air passing through the textile at 100 psi. A higher score indicates higher comfort (more airflow). **(D)** 3-dimensional comfort graph of textiles. Colors are same as above. Arrow direction indicates increasing comfort. **(E)** Heat map of mosquito landing events (red dots). Left is front and right is back. **(F)** Choice tests of mosquito landing events on black vs white sleeve regions. Graphs show mean with standard deviation. Asterisk (*) indicates significance where $p<0.05$.

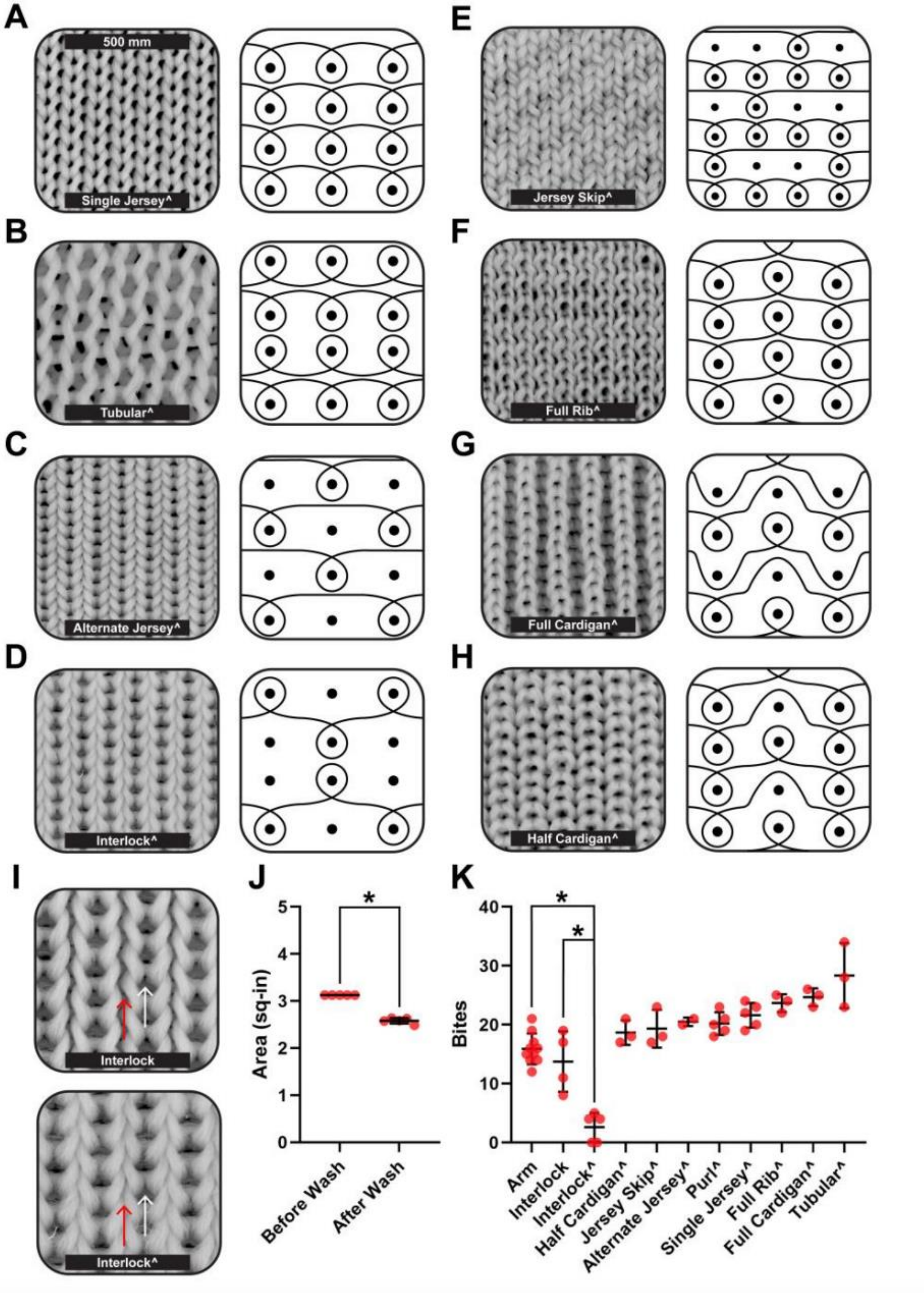

A
500 mm
Single Jersey^
B
Tubular^
C
Alternate Jersey^
D
Interlock^
E
Jersey Skip^
F
Full Rib^
G
Full Cardigan^
H
Half Cardigan^
I
Interlock
Interlock^
J
*
Area (sq-in)
0
1
2
3
4
5
Before Wash
After Wash
K
*
*
Bites
0
10
20
30
40
Arm
Interlock
Interlock^
Half Cardigan^
Jersey Skip^
Alternate Jersey^
Purl^
Single Jersey^
Full Rib^
Full Cardigan^
Tubular^

Figure 3 Microscopy Images and Knit Diagrams of Different Structures. Bite blocking data of all knitted textiles developed at Auburn University using the 100% polyester control yarn of 282 microns. (**A-H**) Microscopy images and knit diagrams of each knit developed. (**I**) Microscopy images of an unwashed (top) and washed (bottom) interlock knit. Arrows are used to highlight significant points of shrinking which enhance the knits bite blocking abilities. (**J**) Graph of total surface area of an interlock textile measured before and after washing. This experiment was conducted 5 times, each dot representing a single interlock piece that was washed, dried, and then measured. (**K**) Graph of the number of bites received during a single 15-minute experiment. Each red dot corresponds to one cage of twenty females and each sleeve was tested a minimum of three times. Carrot (^) indicates washed. Asterisk (*) indicates $p<0.05$.

Chapter 2: Research Findings

2.1 Introduction

Although we could engineer clothing to block mosquito bites, the main challenge was making the textile comfortable. Clothing comfort is a complicated personal perception involving fabric interactions and environmental, physiological, and psychological variables (Wang, 2006). Consumers' perception of apparel products' desirability in all markets is strongly influenced by the level of comfort of the apparel (Kilinc-Balci, 2011). The combination of comfort and mosquito bite blocking has not been mastered until now. The following research explores comfort while fighting against mosquitos and their pathogens.

2.2 Preliminary Experiments and Data

Measuring Comfort

Textile fabrics with functional properties have been around for decades, dating back to rawhide garments (Galante et al., 2003). It is possible to objectively measure fabrics' physical or transmission characteristics, such as thickness, air permeability, thermal transmission, and wicking (Das, 2010). Das used the sensory system of human skin to detect comfort by neurophysiological perceptions (Das, 2010). Comfort is particularly important for functional fabrics since these fabrics are used for special purposes such as sports, military, and medical gear (Tadesse, 2018). In this case, our desired function is blocking mosquito bites. Blind and visual subjective evaluations were common practices for sensory investigations (Tadesse, 2018). In the process of wearing garments, fabric-skin contact is applied to the skin, which in turn causes vigorous mechanical fatigue, or mechanical pressure, to be applied to the skin, which further initiates the various mechanoreceptors and results in a variety of tactile sensations (Tadesse, 2018). This is why humans have an inherent idea of comfort just by the wear. Clothes are made for humans and so to measure comfort there is nothing better than a human's subjective perception of it.

It is important to note that textiles differ from one another in their technical structures in that they must possess sufficient strength, and performance characteristics, while at the same time being flexible, elastic, easy to pleat and shape, and pleasant in both an aesthetic and sensory sense (Zelik, 2012). In order to design clothing for specific applications, a deeper understanding of the interaction between fiber material, yarn structure, fabric structure, transmission characteristics (air, heat, and moisture), and tactile aspects of textile materials can be extremely helpful in understanding thermophysiological and neurophysiological processes related to clothing comfort (Das, 2021).

Cooling Fabrics

When looking for a comfortable athletic shirt, one is looking for breathability and moisture-wicking. The temperature change of fabrics is made of two components: heat transmitted through air spaces and heat that passes through the textile fibers (Baxter, 1946). According to Jim Ross, senior vice president of product development for American Textile Company, cooling fabric dates to NASA's early days when scientists were experimenting with how textiles would affect a spacesuit wearer (Carrie, 2023). The polymer finish (polyethylene) is activated by heat and humidity, which moves moisture away from the fabric (Carrie, 2023). Polyethylene is the most common produced plastic (Zhong et al., 2018). The plastic is extruded to form multiple polymer strands that can be made into textiles (Wang, 2010). Temperature balance is similar to the cooling sensation we experience after a shower as the water (or humidity) evaporates. Boosting the humidity evaporation causes a cooling effect (Carrie, 2023).

There are two main categories of textile cooling technologies: temperature balance and temperature abatement (Carrie, 2023). Temperature balance means maintaining the same temperature (Havenith, 1999). Temperature abatement is the decrease in temperature (Carrie, 2023). Temperature abatement involves the actual transfer of heat. When temperatures are abated, the textile feels cool, even though it is technically not cool by touch. Abation can be applied with the change in yarns, such as PE. Fabrics with highly conductive polyethylene (PE) yarn provide coolness through their conductivity (Carrie, 2023). While wicking technology can be applied to the fabric, the yarn itself is made to cool in this case (Onofreiet al., 2011). Water wicking technology can also be called windows in a textile (Zou et al., 2021). The windows pull moisture to the outside of the textile (Zou et al., 2021). This is created in the knit structure, but certain yarns can speed up the process. A PE yarn can rapidly transfer heat away from the material's surface. (Carrie, 2023). Spandex is made from PE, plastic polymers (Lou, 2011). Today, spandex is used in lingerie, hosiery, leisurewear, and sportswear as a standard fiber (Bhat, 2001). People would consider these items to be delicate, comfortable, and breathable.

2.3 Objectives and Aims

Based on the preliminary data presented above, the research is organized around the following objectives and specific aims:

1. Determine how to quantify human perceptions of comfort.
2. Identify fiber contents of textiles the human instinct recognizes as comfortable and thereafter optimize comfort of bite blocking textiles by mimicking yarn content.
3. Examine which textiles conduct an increase in body heat and re-engineer the textiles with different yarn percentages that will decrease the temperature difference.

4. Demonstrate what textile structures wick water the fastest in two different methods. And determine if yarn fiber percentages change can speed up the amount of water wicked.
5. Test if air permeability correlates with mosquito blocking and comfortability.

2.4 Materials and Methods

Knitting Methods

M1 Plus was created by Stoll as a knitting program used for their products. The program creates files that are entered in the Stoll ADF 530-16 Ki BcW Flatbed via flash drive. M1 Plus is an all-inclusive program that permits a researcher to input knit diagrams that can be read by the computer numerical control (CNC) knitting machine. Nearly every knit tested in this research was constructed at Auburn and produced from this program. The files are generated by using different repetitions of front and back loops to develop complex patterns and knit structures (Fig 1). M1 Plus allows for high creativity if the parameters fit within the encoded parameters. Stoll ADF 530-16 Ki BcW is a flatbed knitting machine. The finished fabric will be a flat sheet with seams along the sides. The machine has two beds of needles, one on the front and one on the back, as opposed to circular knit machines only one bed. Circular knit machines are used to knit tubular items. By using the flat bed machine, textiles can be produced more intricate. This machine produced most fabrics experimented with in my research. The parameters of this machine may be varied, just as they are on the M1 Plus. The parameters are stitch length, run speed, and fabric size.

We created test sleeves for mosquito bite experiments using a Brother International CS7000X Sewing Machine. The sleeves are created by sewing flat sheets of fabric from the Stoll Flatbed Knitting Machine together. The sleeves were made to fit an experimenter’s arm measurements. Upon completing each sleeve, a Brother International 1034D Serger Machine is used to create hems and finish the raw edges.

There were multiple yarns used. The yarns are measured by denier which is the unit of weight in grams of 9,000 meters (Tascan, 2008). This is often used to describe the thickness. The 100% polyester yarn was 2/150/96 in size (number of plies/denier of each ply/number of filaments in each ply). The Black Spandex Poly Blend yarn was 1/150/136 in size (number of plies/denier of each ply/number of filaments in each ply). The Recycled Spandex Poly Blend yarn was 1/150/68 in size (number of plies/denier of each ply/number of filaments in each ply). The 20% Spandex and 79.8% Nylon yarn was 1/40/34 in size (number of plies/denier of each ply/number of filaments in each ply). The 100% Nylon yarn was 1/70/34 in size (number of plies/denier of each ply/number of filaments in each ply). All yarns were acquired from Unifi, inc. Based in Greensboro, North Carolina, Unifi is a fiber and yarn production company that specializes in the development of textiles.

Comfort Testing

One intention of this research was to determine a quantifiable means of assessing the perception of human comfort with respect to textiles. Scientists might disagree on whether the perception of comfort is subjective or objective. If comfort is subjective, humans across cultures and ethnicities would not agree on what is comfortable. If comfort is objective, most humans would form a consensus on what was perceived as comfortable. To add complexity, comfort is also determined by fit. A comfortable garment might be uncomfortable if it is too small, etc. In this case we define comfort as the inherent perception/feeling a human has when their skin touches the textile and not the fit of a garment. Studies have shown that comfort is subjective across world cultures and ethnicities (Lee et al. 2003). However, this thesis begins a discussion on this topic in the Alabama region; in order to complete comfort analysis, we do assume that perceived comfort of our textiles would be a consistent, measurable, and useful value to assess the pros and cons and engineering/optimization of mosquito bite blocking textiles (Wilfing et al., 2021). Most readers would find this assumption logical and if not, at least testable, and thus scientifically worthy of study.

In order to test human comfort our strategy was to allow a human to interact with a textile via touch. Compare touch of the test fabric to that of two control fabrics. Then rank the test fabric on a scale of 1-10 with 1 being high comfort and 10 being low comfort in response to a descriptive adjective, like “gritty” for example (Fig 4). A total of 31 textiles made up of different yarns and structures were evaluated by volunteers on a hand feel panel. The assessment of the hand feel credit was done by a spectrum skin feel panel consisting of 20 volunteers. These volunteers have no background in textile studies and range from 20 years old to 35 years old. In order not to bias the experiment, experimenters received no training before hand and no questions were answered to them when in progress. In addition, experimenters were blind to which textile they were providing subjective analysis of. The purpose of these measurements is that humans have an innate sense of what feels comfortable to their skin (Tadesse et al, 2018). This survey experiment enables true answers from various people without bias. These tests are standard measures of comfort in the textile industry and contain nine discrete factor subcomponents of comfort (Sztandera, 2012). Two textiles (which are considered extremes of each factor) are used as controls to determine the maximum and minimum values of the scale. The nine factors and definitions being tested are: Gritty – the amount of small, abrasive, picky particles on the surface of the sample. Gritty textiles are less comfortable. Fuzzy (circular motion) – the amount of pile, fiber, and fuzz on the surface of the sample. Less fuzzy textiles are less fuzzy. Thickness – perceived distance between the thumb and the index finger (when the sample is placed between the two). Thick fabrics are less comfortable than thin. Perceived tensile stretch – degree to which the sample stretches from its original shape. Less stretchy textiles are less comfortable. Perceived hand friction – force required to move the palm of the hand across the surface of the sample. High friction fabrics are less comfortable. Fabric to fabric friction – force required to move the fabric over itself. Fabric that scratches against itself is less comfortable. Force to compress – amount of force required to compress the gathered sample into the palm. More compressible fabrics are more comfortable. Stiffness – degree to which the sample feels pointed, ridged, and cracked; not pliable. Stiff fabrics are less comfortable. Noise intensity – loudness of the noise pitch/frequency of the noise caused by feeling the fabric (Sztandera, 2012). Loud fabrics are perceived as less comfortable. Volunteers should have similar subjective answers with tight variance amongst experimenters if the subjective perceptions are intuitively valid. These experiments were performed in at least triplicate with three independent experimenters.

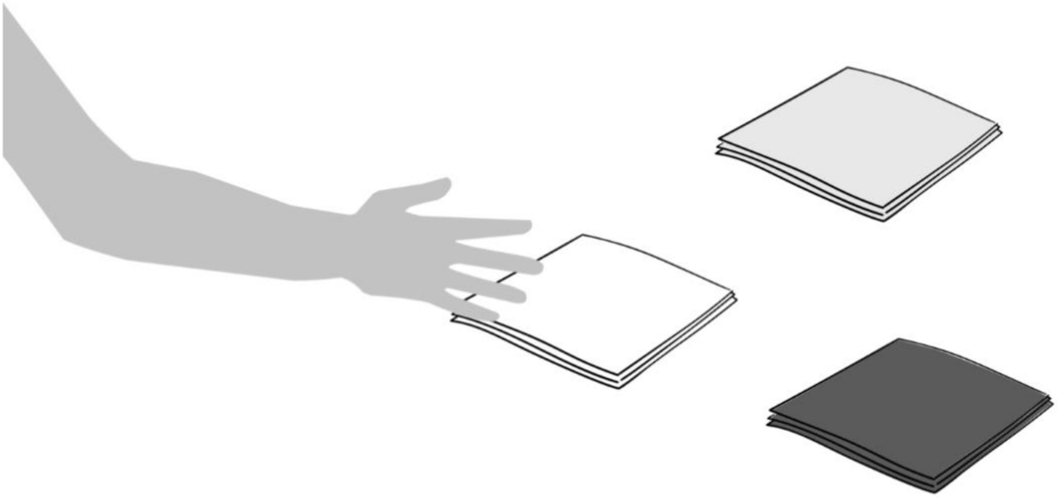


Figure 4 Comfort Hand Feel Test. This picture is an illustration of the hand feel test. Physical comfort is measured by the hand feel test. On a scale of one to ten, nine factors are assessed in this test (Sztandera, 2012). To determine the maximum and minimum values of the scale, two textiles are used as controls. The nine factors being tested are gritty, fuzzy, thickness, tensile stretch, hand friction, fabric-to-fabric friction, force to compress, stiffness, and noise intensity.

Temperature Difference Test

Hot weather textiles are more comfortable if they permit heat to pass through and cool the wearer. We measured temperature difference of textiles on actual humans via the following experiment. A participant wears a sleeve on their arm and enters a 28°C (70% relative humidity) incubator for 15 minutes. A total of four digital thermometer readings were taken by iProven No-Touch Thermometer NCT-336, two before (on the skin and sleeves) and two after incubation (on the skin and sleeves) (Fig 5). Heat gain is calculated by calculating the difference in temperature between the skin and sleeves after the experiment has been completed. These experiments were performed in at least triplicate. The equation used is Delta T = T2 - T1.

Figure 5 Temperature Difference Test. This figure illustrates the steps in the temperature different test. An initial temperature is taken before the sleeve is worn and then the temperature is taken again after taking the sleeve off leaving the incubated room.

Our insectary is housed inside a walk in Darwin incubated chamber kept at 28°C (70% Relative Humidity). This room was used for all water-wicking experiments and temperature difference testing. The walk-in incubator simulates a hot humid day and thus was optimal for performing comfort experiments in conditions favorable to mosquitos.

Water Wicking Test without Sponge

Moisture-wicking clothing allows sweat to easily evaporate. The evaporation provides a cooling sensation that is designed to be comfortable in hot environments. The water wicking test is completed in 2 ways. The first experiment is tested without a sponge. A fabric square, measuring 3 by 3 inches, was weighed, and placed on a black tray (Fig 6A). The VWR® T-Series Balances with Calibration Certificate Scale was used because it has a precise readability of 0.01mg. An addition of 100 mL of water is added to the fabric and distributed evenly on the surface. After we get the weight of those combined, the fabric on the tray will sit in an incubator held at 28°C (70% relative humidity) for 30 minutes. After the time is up the fabric is weighed again to find the total water lost via evaporation. Textiles that lose more water should in theory be more comfortable because water evaporation leads to cooling. The pros of this experiment are that it measures only effects sourced to the textile. The con of this experiment is that actual textiles water wick while in contact with human skin. Perspiration must pass through the textile from the bottom up. Thus, to more accurately mimic measurements of human sweat we designed a secondary experiment below.

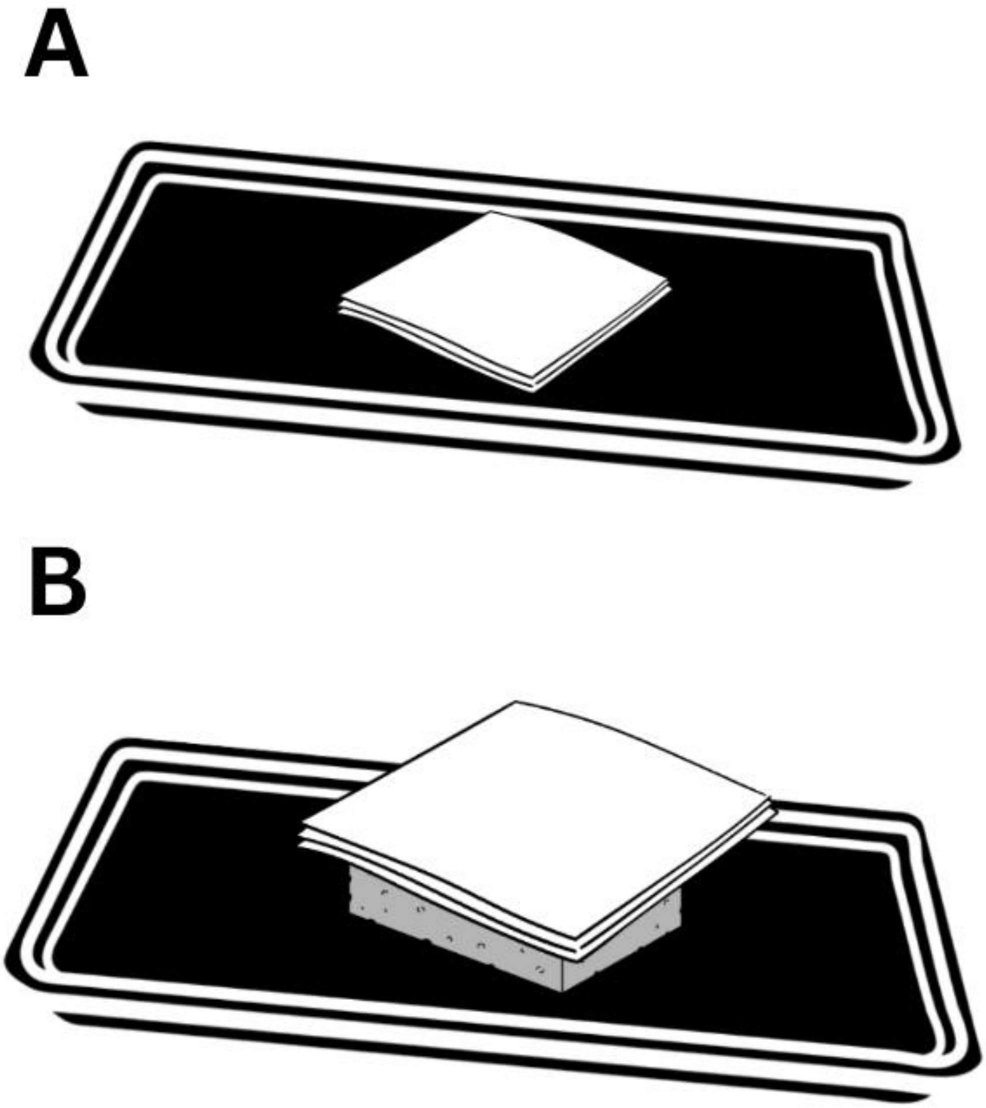


Figure 6 Water Wicking Tests. (A) Illustration of the water wicking test (with no sponge). A 3 by 3 inches textile covered evenly by 100 mL of water. The textile sits in an incubated room for 30 minutes and then measured as one for total water loss. The total experiment is measured by a scale for total water loss. **(B)** Illustration of the water wicking test (with sponge). A 3 by 3 inches textile is placed over a submerged sponge. The water must travel through the textile to evaporate. The experiment last for a total of 30 minutes in an incubated room. The sponge and textile are then measured by a scale for total water loss.

Water Wicking Test with Sponge

Water wicking is the water or sweat that evaporates through a textile, so an alternate test was demonstrated to capture this action. The other water-wicking test requires half of a sponge. A sponge is cut exactly down the middle. The sponge is then submerged in tap water for 10 seconds and then lifted directly up out of the water. The sponge then drips for a count of 10 seconds. By this time, it always stopped dripping. The sponge is then placed on a black tray to be measured for weight. A fabric square, measuring 3 by 3 inches was weighed and placed on top of the sponge covering all exposed sides of the sponge (Fig 6B). The same scale is used, the VWR® T-Series Balances with Calibration Certificate Scale. After the combined weight is measured, the fabric on the tray will sit in an incubator held at 28°C (70% relative humidity) for 30 minutes. After the time is up, everything together is weighed, and then individual items are also weighed separately. After the measurements, the total water loss is calculated. As above, textiles that lose more water should be perceptually more comfortable as they would provide enhanced cooling through evaporation.

Air Permeability Test

An article of clothing's air permeability indicates how well it can breathe. Therefore, we sought to measure the air permeability of textiles. This experiment was conducted on a black table incrementally marked in inches with 20 grams of salt on the edge sitting next to the textile. By passing a burst of compressed air at 100 psi from a Kobalt 6-Gallon Single Stage Portable Corded Electric Pancake Air Compressor, through the framed textile, we can measure air permeability by quantifying its ability to move a substrate (20 grams of salt) a given distance in inches along the black table (Fig 7).

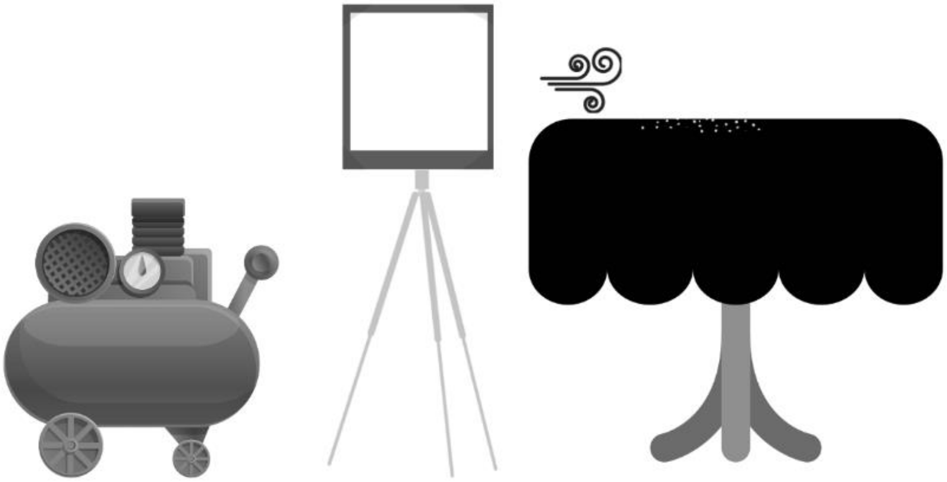


Figure 7 Air Permeability Test. Illustration of the air permeability test. This experiment is measured by passing compressed air at 100 psi through the textile, measuring its ability to move a substrate (20 grams of salt) over a given distance. The distance traveled by the farthest gram of salt is recorded.

Microscopy

A Nikon SMZ1270 stereomicroscope was used in conjunction with a Nikon DS-Fi3 camera to capture all microscopy images. Pictures were taken to show the knit structures after being knitted (Fig 3). Scale bars used in microscopy figures were created by using a millimeter ruler during imaging. A scale bar was made in photoshop and added to each figure.

Statistics

A variety of software programs have been used to record and analyze the data, including GraphPad Prism 9 and Microsoft Excel. The data were analyzed using two different statistical methods. We first performed Ordinary One-Way ANOVAs and Tukey's multiple comparisons tests for any experiments that yielded more than two sets of results. An unpaired, nonparametric Mann-Whitney t-test was used for experiments with only two data sets. This was used for the individual comfort scores. Polyester Interlock and Under Armour were the two textiles compared to each other. Significant comparisons are those that yield a P-value less than 0.05.

Mosquito Rearing

We reared *Aedes aegypti* mosquitoes in a clean laboratory free from disease pathogens. During the development process, mosquitoes were kept in an incubator at 28°C with a 12-hour light/dark cycle. A mosquito egg is hatched by submerging it in a medium-sized shoebox tub until it develops into a pupa. We feed larvae and pupae a mixture of yeast and water that contains approximately 5 mL. Pupae are transferred by hand into a mesh cage for closure. To control the pupae age, pupae are allowed to enclose for 72 hours and then removed and placed in a new cage. Four to seven-day-old female mosquitoes were used in the mosquito-biting experiments.

2.5 Results

As detailed above, an overarching objective of my thesis was to determine how to quantify the human perception of comfort with respect to mosquito bite blocking textiles. Tests (described in methods) were then conducted to assess human perception of a 9-factor comfort perception analysis, temperature differential, water wicking, and air permeability. Overall, the results below overwhelmingly converged on the fact that a Spandex/ Nylon blend scored best on most tests of comfort. 20 individuals reported comfort perceptions in response to the comfort test analysis; these individuals showed clear preferences for discrete textiles that were consistently viewed as more comfortable amongst them. In combination with the comfort perception analysis, we performed additional empirical measurements that could corroborate the human perceptions of comfort. Textiles that were perceived as more comfortable were also showed the most comfortable empirical data when measured with water wicking, air permeability, and temperature differential tests. Thus, all the comfort tests converged with each other. In each test other than air permeability, the Spandex/Nylon blend had the best ranking scores. Spandex/ Nylon was not tested in air permeability experiments. Thus, I suggest that mosquito blocking garments can be made more comfortable. Thereafter, the goal of my research was to engineer the most comfortable blocking textiles through permutations that would improve the perceptive feel. Through the following analyses and within this chapter I describe what yarns and fibers will increase comfort scores of the downstream textiles.

Comfort Test Reveals Which Textiles Score Highly in Comfort.

A survey was conducted with twenty individuals for 5 minutes with an even split of males and females. At first only 8 polyester textiles and one acrylic textile were measured and shown in individual characteristic scores (Fig 8). This is because as the survey's progressed the data indicated that the textiles needed to be made more comfortable and thus our approach was simultaneously accompanied by engineering work to knit the same textile structure with different fibers. As more textiles were produced, more knits were necessarily added to the surveys. The purpose of these experiments was to determine which factors specifically contribute to comfort and which ones could be optimized. Our blocking textile, interlock, scored low and required improvement in a few areas. The low scores were in perceived thickness (overly thick textiles are not typically considered comfortable to wear), tensile stretch (stretchy textiles are considered more comfortable), and stiffness (less stiff textiles are perceived as more comfortable) (Stevens, et al., 2025) (Sztandera et al., 2012).

After performing the 9 individual sub-factor perceived comfort tests, we sought to normalize the measurements into an overarching combinatorial comfort score. We chose to weight all 9 sub-factors equally for this thesis, though future studies might investigate which of these measurements is more valuable and should be given more weight in comparison to others.

In total, a combination of eight knitted geometries with permutations of three to five different yarn contents/percentages were knitted and tested. This made a total of 29 textiles and two control textiles. The five yarns used were, polyester, recycled spandex, spandex, nylon, and a Spandex Nylon blend. Polyester is known to have high strength and good heat resistance (Hillmyer et al., 2014). Spandex is used for athletic and aerobic clothing, due to its elasticity and recovery (Singha, 2012). Nylon has high tensile stretch and high strength (Song et al, 2005). These performance properties are the reasons why these yarns were tested. After comprehensive testing it was clear that volunteers overall preferred Spandex/Nylon yarn as the most comfortable yarn (Fig 9). The most comfortable textiles measured were Spandex/ Nylon Interlock and Spandex/ Nylon Half Cardigan (Fig 9). All these permutations were statistically compared against a control interlock knit with polyester because this was our original blocking knit that needed comfort optimization. The following knits are more comfortable than the Polyester Interlock. The Spandex/ Nylon Interlock compared to Polyester Interlock control had a significant difference of p = .0013. Knit structures that did not block after the introduction of spandex were discontinued (Fig 10).

In previous research, non-blocking knits could be converted to blocking knits by either the addition of spandex or a thicker fiber filament (Holt et al., 2023). Our research did uncover new combinations that converted two knits from non-blockers to blocking. These knits were Half-Cardigan and Single Jersey with Spandex/Nylon additions. The Spandex/Nylon Interlock blocked 100% of mosquito bites, Spandex/Nylon Half- Cardigan blocked 88% of mosquito bites, and Spandex/Nylon Single Jersey blocked 95% of mosquito bites. The original Polyester Interlock had a 92% blocking ability, Polyester Half-Cardigan had a 11.67% blocking ability, and Polyester Single Jersey had a 7% blocking ability. Overall, we constructed many knits and over the course of the research and in addition to discovering knits that could be converted into blocking knits we found that other knits could not be converted to blockers by the addition of the yarns we had access to. It was beneficial to cease experimentation on knits that were not promising blockers, even after the addition of spandex. Thus, we discontinued comfort testing on Full Rib, Full-Cardigan, Alternate Jersey, Jersey Skip, Purl, and Tubular.

In addition, the perceived comfort data were quite useful in that we started to eliminate knit structures and particular combinations from testing when we saw no change in blocking and no increased comfort. Thus, by utilizing the perceived comfort scores we were able to quickly screen through diverse fiber options to settle on the most comfortable combination for further testing.

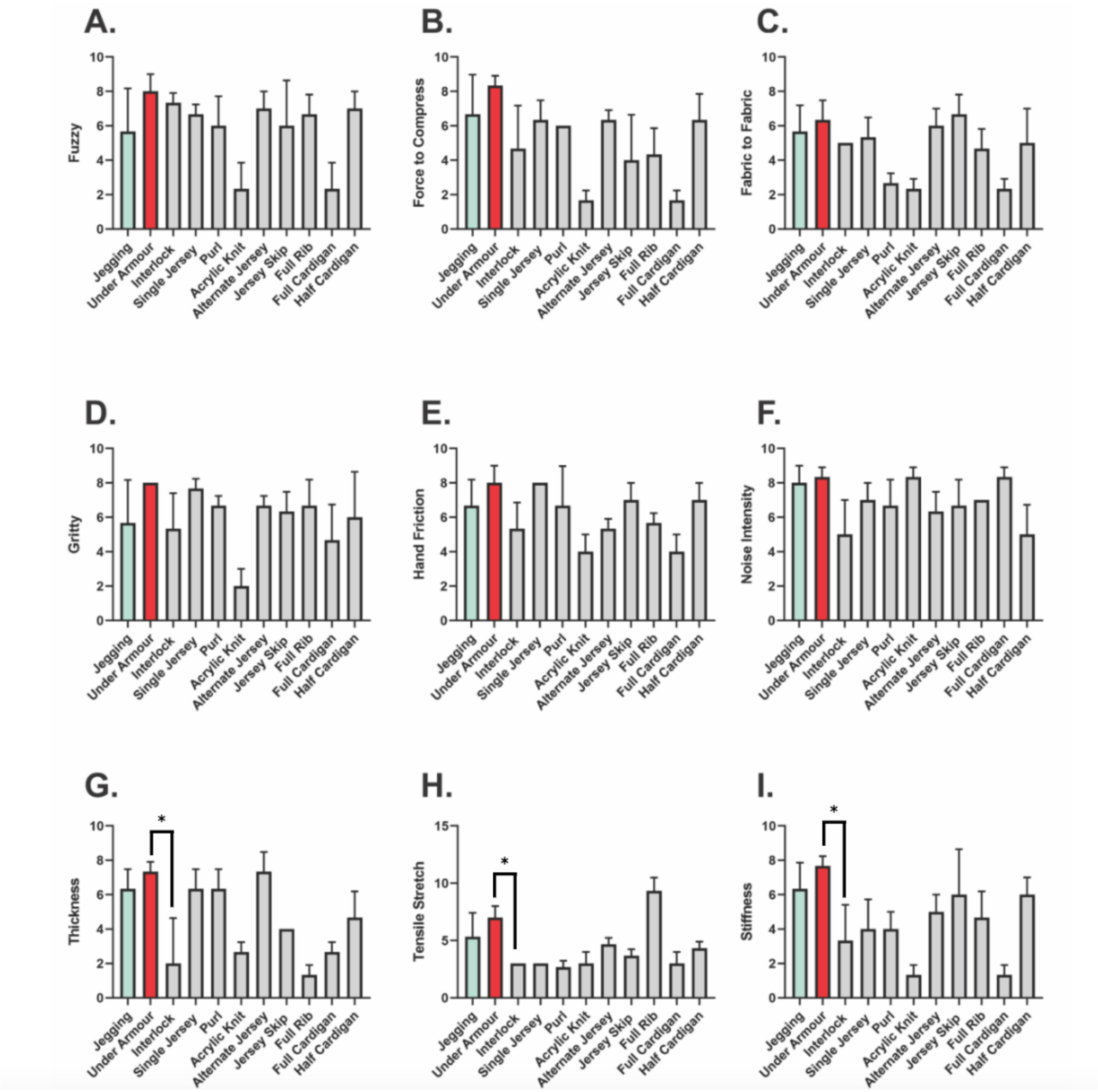


Figure 8 Individual Comfort Hand Feel Test Graph. Discrete data from 9 factor determinants of comfort. Graphs are mean with standard deviation. Increased scores correlate with increased comfort. Interlock showed a significant difference in thickness, tensile stretch, and stiffness compared to Under Armour (Holt et al., 2023). Asterisk (*) indicates significance where $p<0.05$.

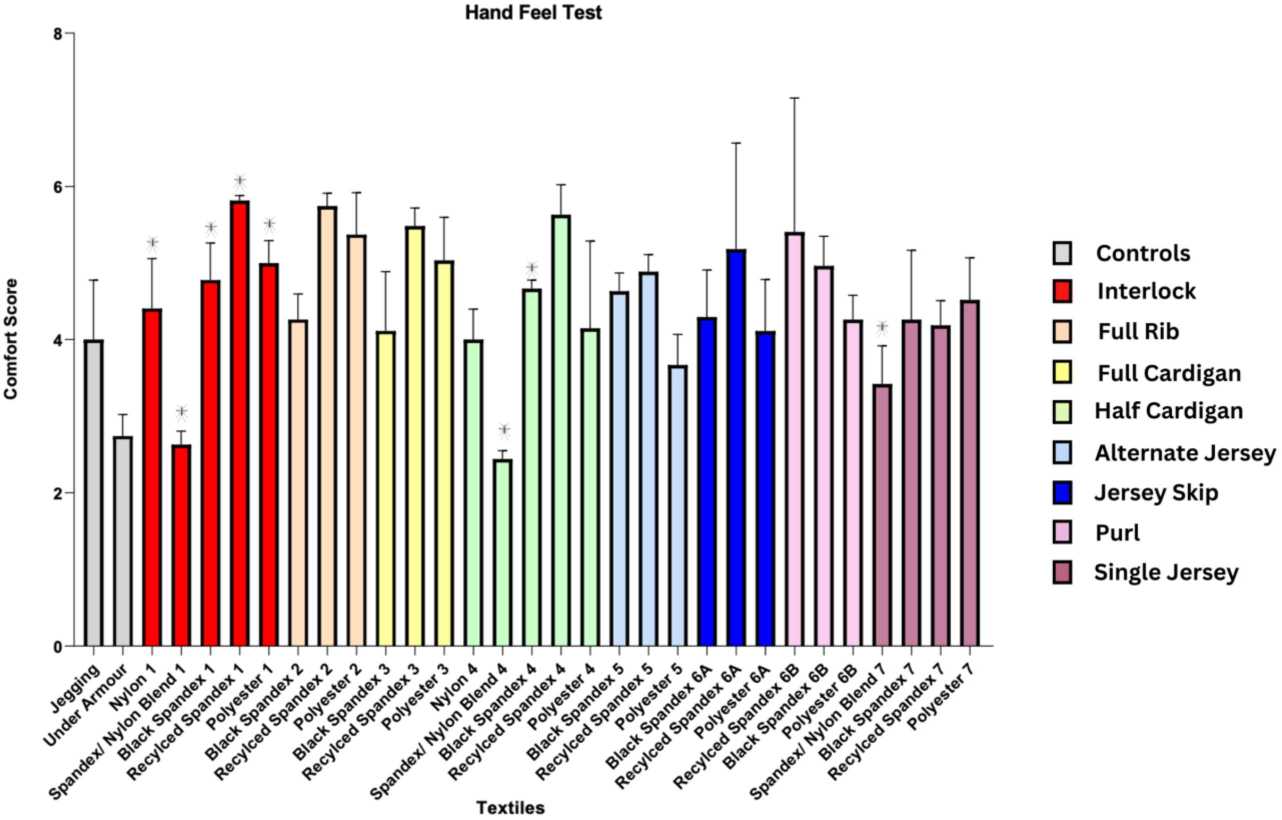


Figure 9 Comfort Hand Feel Test Graph. There are nine comfort factors that are averaged out to determine the most comfort textiles. The graph is presented as means with standard deviations. A low comfort score is correlated to high comfort. Low scores are best. The small mosquitos above the bar represent blocking textiles.

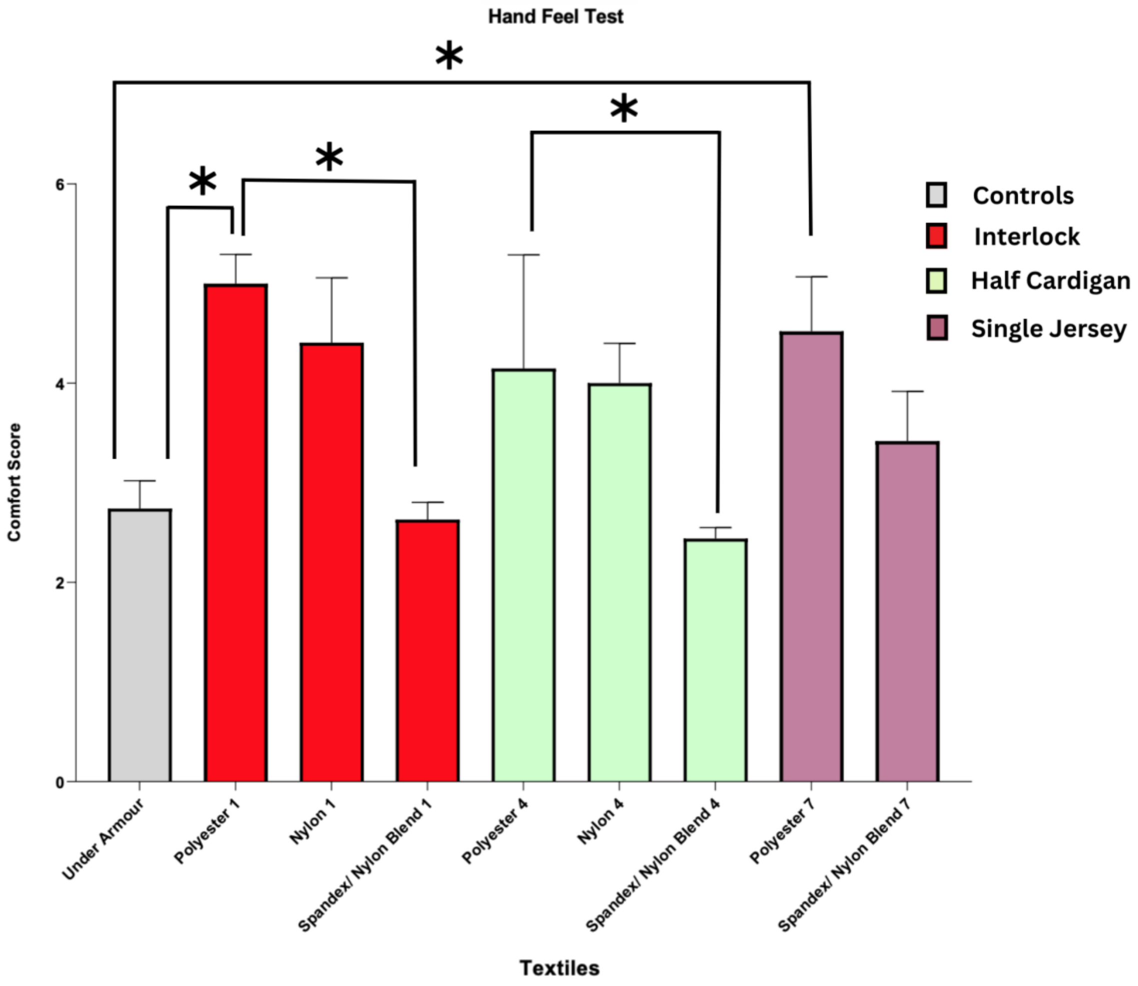


Figure 10 Comfort Hand Feel Test Significant Difference. There are nine factors that are averaged to determine the most comfort textiles. The selected textiles show the increase in comfort made from the original Polyester textiles. The graphs are presented as means with standard deviations. An increase in comfort is correlated with a decrease in scores. Low scores are best. Asterisk (*) indicates significance where $p<0.05$.

Temperature Difference Testing Reveals Which Textiles Permit Heat Loss.

A test was conducted for 15 minutes each trial. A total of 31 textiles were measured to see if a human's body temperature would increase due to the textile sleeve. These scores were used in comparison to four controls, bare arm, jegging, Under Armour, and cotton sweatshirt (Fig 11). The purpose of this experiment was to determine which textile structures specifically contributed to heat gain and which ones could be optimized. The less heat gains the lower the score, making it a comfortable textile. Our blocking textile, interlock, started off with low score until nylon or spandex was used, but the combination of nylon and spandex brought the score back down. Hot weather textiles are more comfortable if they permit heat to pass through and cool the user. A reminder that mosquitos live in hot humid climates so low scoring textiles would be ideal. The reason for this method of testing is to get actual data from flesh and experience what users would encounter.

As a result of the experiment, the difference in temperature between the skin and sleeve is determined and these values are shown on a graph as heat gained (Fig 11). The three lowest scores were Spandex/ Nylon 1, Recycled Spandex 1, and Spandex/ Nylon 7. No significance was found in this experiment between the structures and Under Armour (Fig 12). Not significant result is a good result because they are permitting as much heat loss as Under Armour. In conclusion the addition of Spandex/Nylon improves the heat loss.

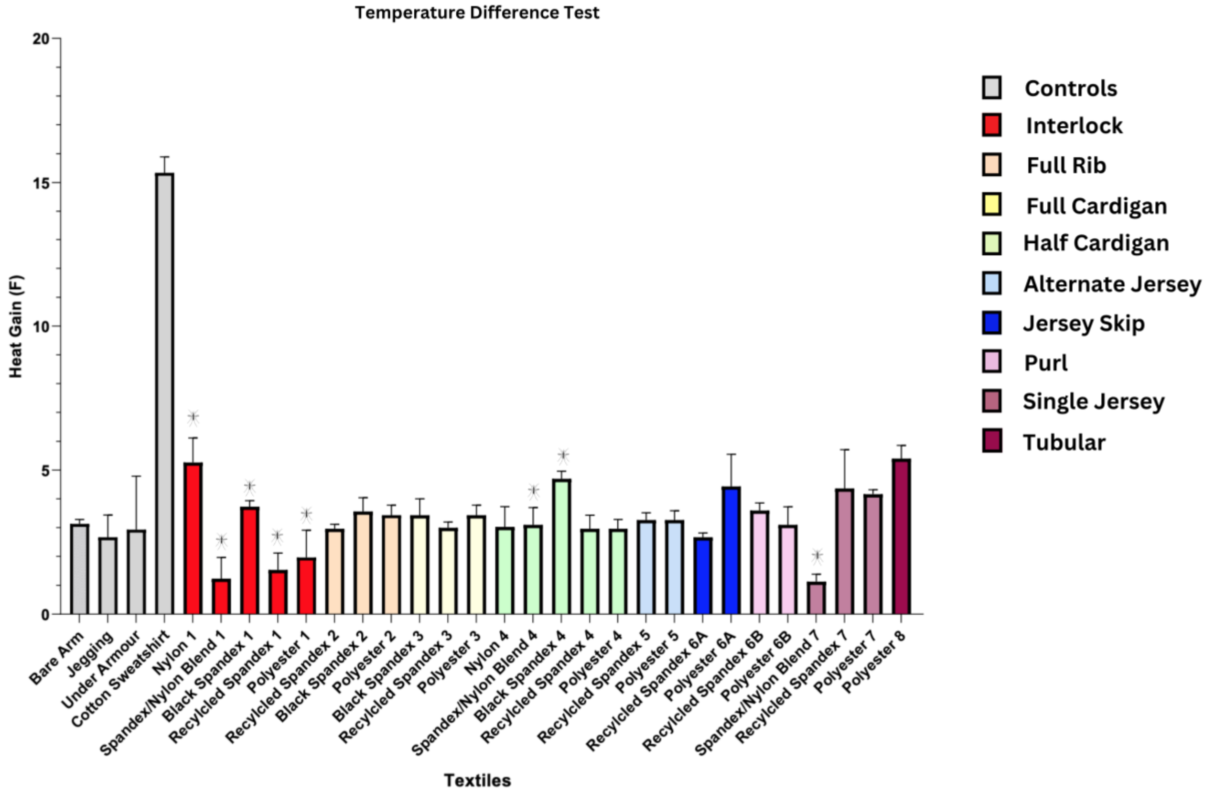


Figure 11 Temperature Difference Test Graph. Each textile was measured in a temperature difference test. Each bar represents three replicates performed. The graph is presented as means with standard deviations. A low temperature change is good. The small mosquitos above the bar represent blocking textiles.

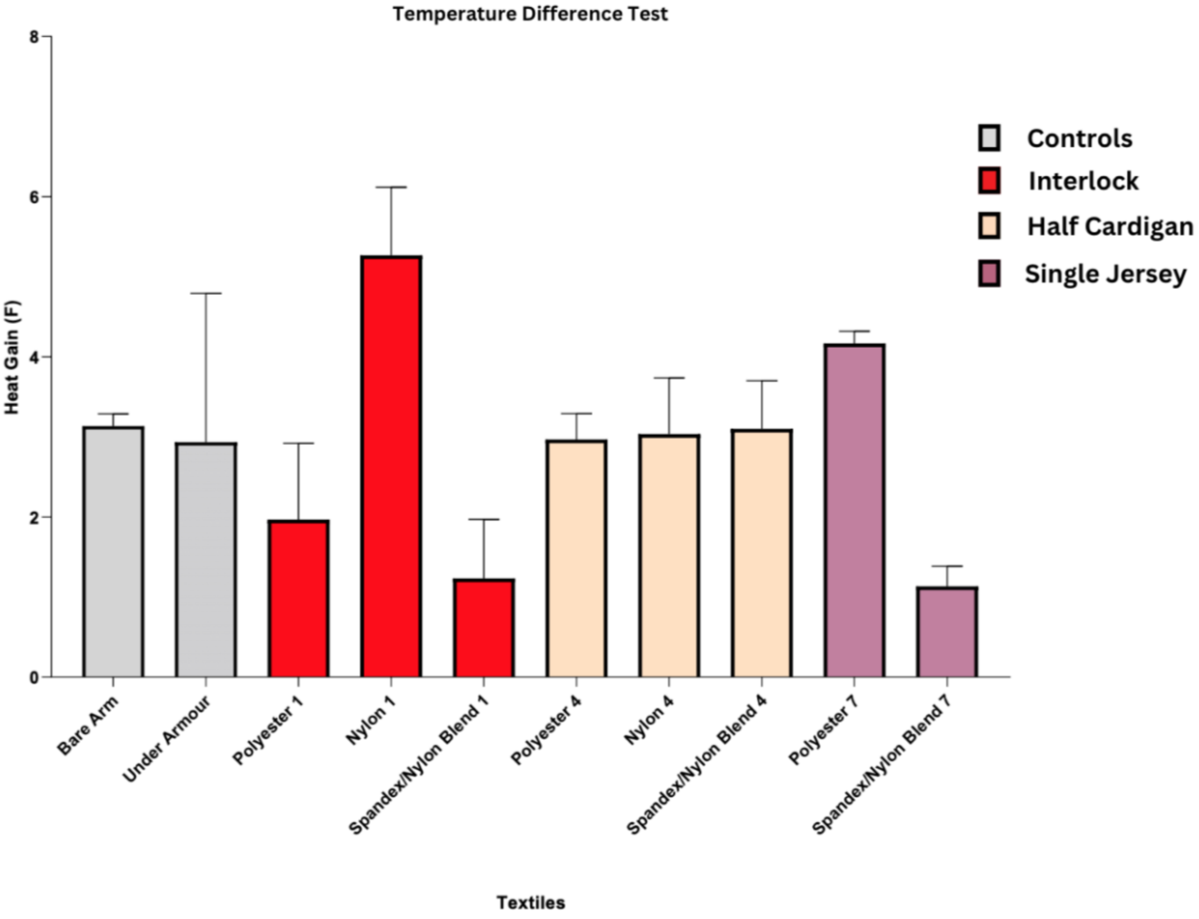


Figure 12 Temperature Difference Test Significant Difference. Each textile was measured in a temperature difference. The selected textiles did not demonstrate significant difference. The graphs are presented as means with standard deviations with three replicates. A low temperature change is good. There was no significance made from this experiment.

Water Wicking with no Sponge Testing Reveals Which Textiles Wick Away Water the Fastest.

These scores were used in comparison to two controls, jegging and Under Armour (Fig 13). The purpose of this experiment was to determine which textile structures specifically contributed to water loss and which ones could be improved. The more water loss the higher the score, making it a fast water wicking textile. Our blocking textile, interlock, started off with average scores. When nylon or spandex was used not much changed in scores besides Nylon's score decreasing. It was not until the combination of the two, nylon and spandex, that increases the water loss in comparison to the controls. When Nylon/Spandex was used, almost all the water had evaporated. Nylon/Spandex demonstrates excellent wicking property. This test was conducted to show which textiles would perform best in hot humid climates and cool the body when sweating. Fast water wicking is a sign of moisture comfort (Fashandi et al., 2017).

In this experiment the blocking textiles that scored the highest were Spandex/ Nylon Interlock, Spandex/ Nylon Half Cardigan, and Spandex/ Nylon Single Jersey (Fig 13). The Spandex/ Nylon Interlock comparison to Polyester Interlock had a significant difference of p = <.0001, and Spandex/ Nylon Interlock compared to Under Armour had a significant difference of p = <.0001. These stats show improvement from the original Polyester while also outperforming Under Armour. The Spandex/ Nylon Half Cardigan compared to Polyester Half Cardigan had a significant difference of p = <.0001, and Spandex/ Nylon Half Cardigan compared to Under Armour had a significant difference of p = <.0001. Similar to the previous pattern, Spandex/Nylon was an improvement from Polyester while significantly being different in a positive way to Under Armour. The Spandex/ Nylon Single Jersey compared to Polyester Single Jersey had a significant difference of p = .0006, and Spandex/ Nylon Single Jersey compared to Under Armour had a significant difference of p = <.0001. Every time Spandex/Nylon was used there was a large positive significant difference in performance from its original state, Polyester.

Regular 100% Nylon did not have a significant difference compared to Under Armour or Polyester (Fig 14). An interesting conclusion is that neither Spandex nor Nylon independently improved water wicking. However, the combination of the two created a synergic effect that improved the water wicking ability of water wicking of the textile.

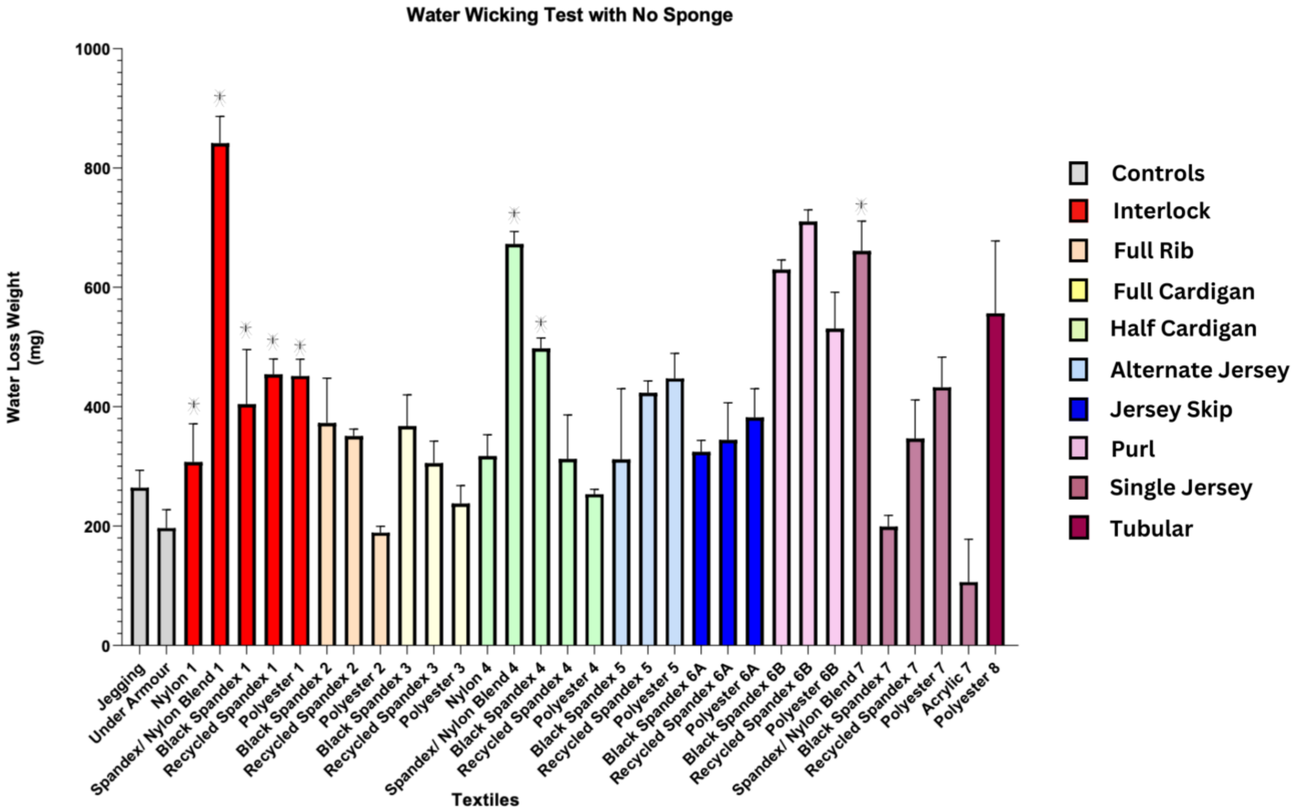


Figure 13 Water Wicking with no Sponge Test Graph. Each textile was measured in a water wicking test with no sponge. Each bar represents three replicates performed. The graph is presented as means with standard deviations. High water loss is good. The small mosquitos above the bar represent blocking textiles.

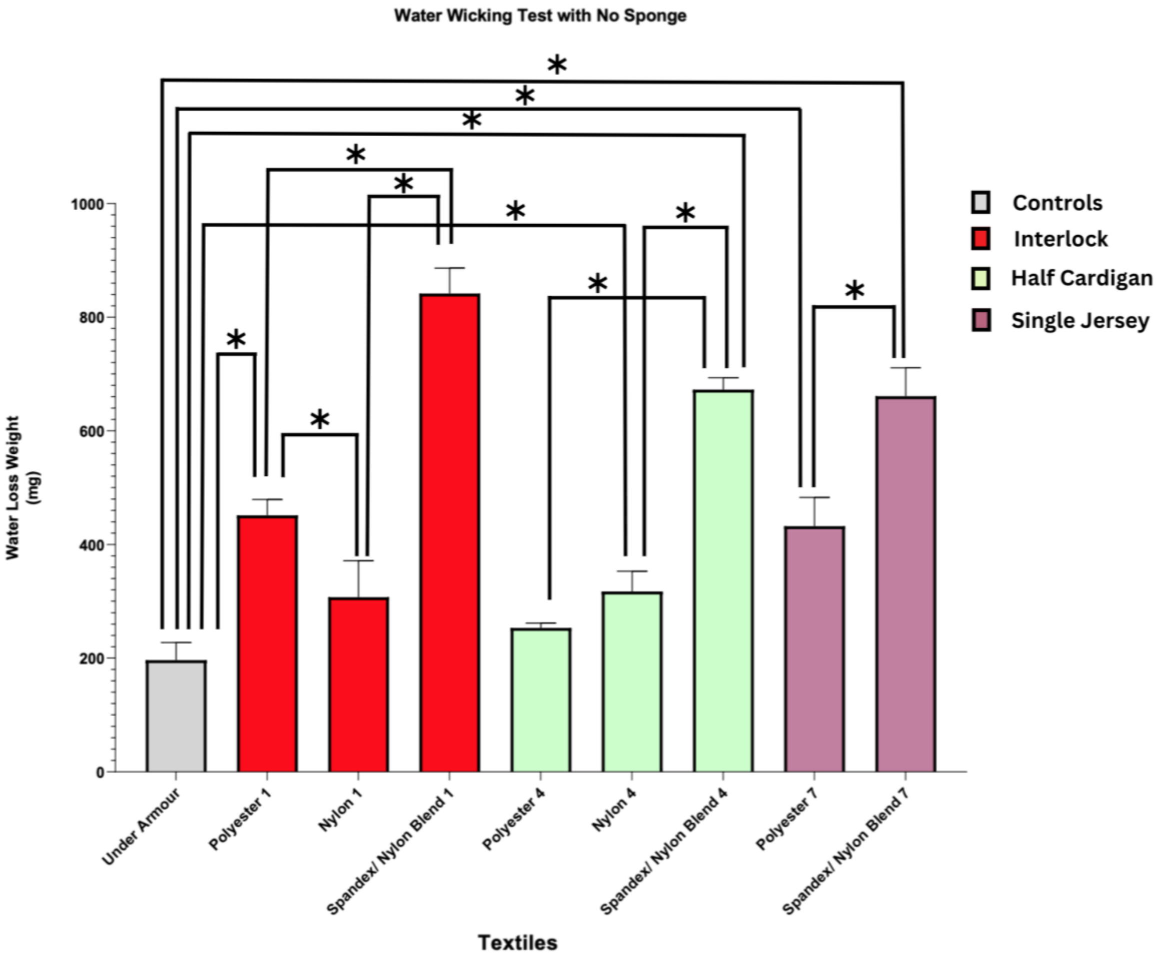


Figure 14 Water Wicking with no Sponge Significant Difference. Each textile was measured in a water wicking test with no sponge. The selected textiles show the increase of water loss made from our original Polyester textiles. The graphs are presented as means with standard deviations. An increase in water loss is correlated with an increase in scores. High scores are best. Asterisk (*) indicates significance where $p<0.05$.

Water Wicking with Sponge Testing Reveals Which Textiles Wick Away Water the Fastest.

A similar test to the prior water wicking experiment contained a new modification. A sponge was added to serve as a reservoir of water. In this case a water must pass from the sponge through a textile in order to evaporate. This modification was added to mimic a body sweating. The purpose of this test was to see if the scores are similar to the other test and to determine which textile structures specifically contributed to water loss and which ones could be improved. There were a few textiles that did not perform well in this test. All the polyesters had lower scores. Polyester Tubular was one of the worse on this experiment because of it being a two layered textile. In this case the water had to travel through two layers, because tubular is a two layered structure. Spandex/Nylon performed similar to the last experiment. This second test has backed Spandex/Nylon up on being an excellent wicking textile.

In this experiment the blocking textiles that scored the highest were Spandex/ Nylon Interlock, Spandex/ Nylon Half Cardigan, and Spandex/ Nylon Single Jersey (Fig 15). The Spandex/ Nylon Interlock compared to Polyester Interlock had a significant difference of p = <.0001, and Spandex/ Nylon Interlock compared to Under Armour had a significant difference of p = <.0001. There is substantial growth from where we started with polyester and moved to Spandex/Nylon. The Spandex/ Nylon Half Cardigan compared to Polyester Half Cardigan had a significant difference of p = <.0001, and Spandex/ Nylon Half Cardigan compared to Under Armour had a significant difference of p = <.0001. Here we see the same continuation of water loss when using Spandex/Nylon. The Spandex/ Nylon Single Jersey compared to Polyester Single Jersey had a significant difference of p = <.0001, and Spandex/ Nylon Single Jersey compared to Under Armour had a significant difference of p = <.0001 (Fig 16). We use Under Armour as our control because they claim to be a comfortable textile that wicks away water fast (*Men's heatgear® fitted long sleeve*, 2023). Our Polyesters were to show where we have started, and the Spandex/Nylon is where we are now. This experiment was important because it shows substantial improvement in water wicking capability.

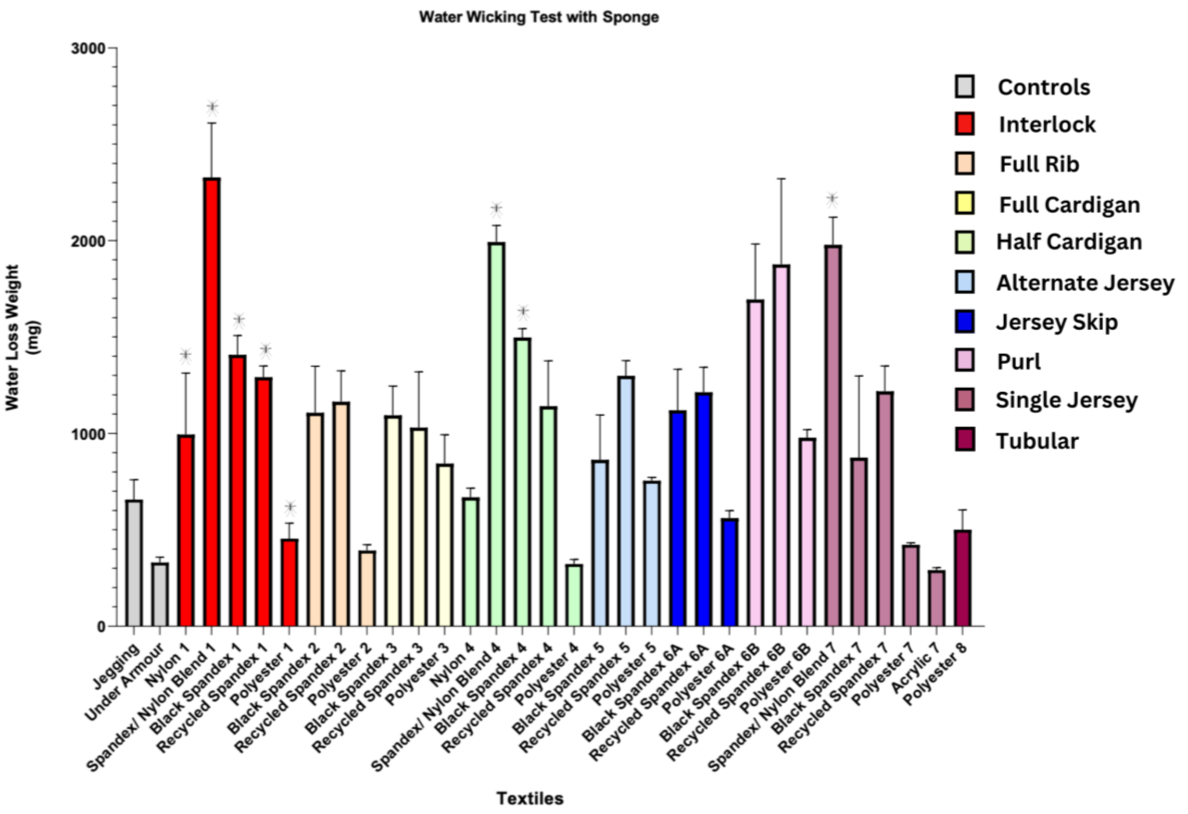


Figure 15 Water Wicking with Sponge Test Graph. Each textile was measured in a water wicking test with sponge. Each bar represents three replicates performed. The graph is presented as means with standard deviations. High water loss is good. The small mosquitos above the bar represent blocking textiles.

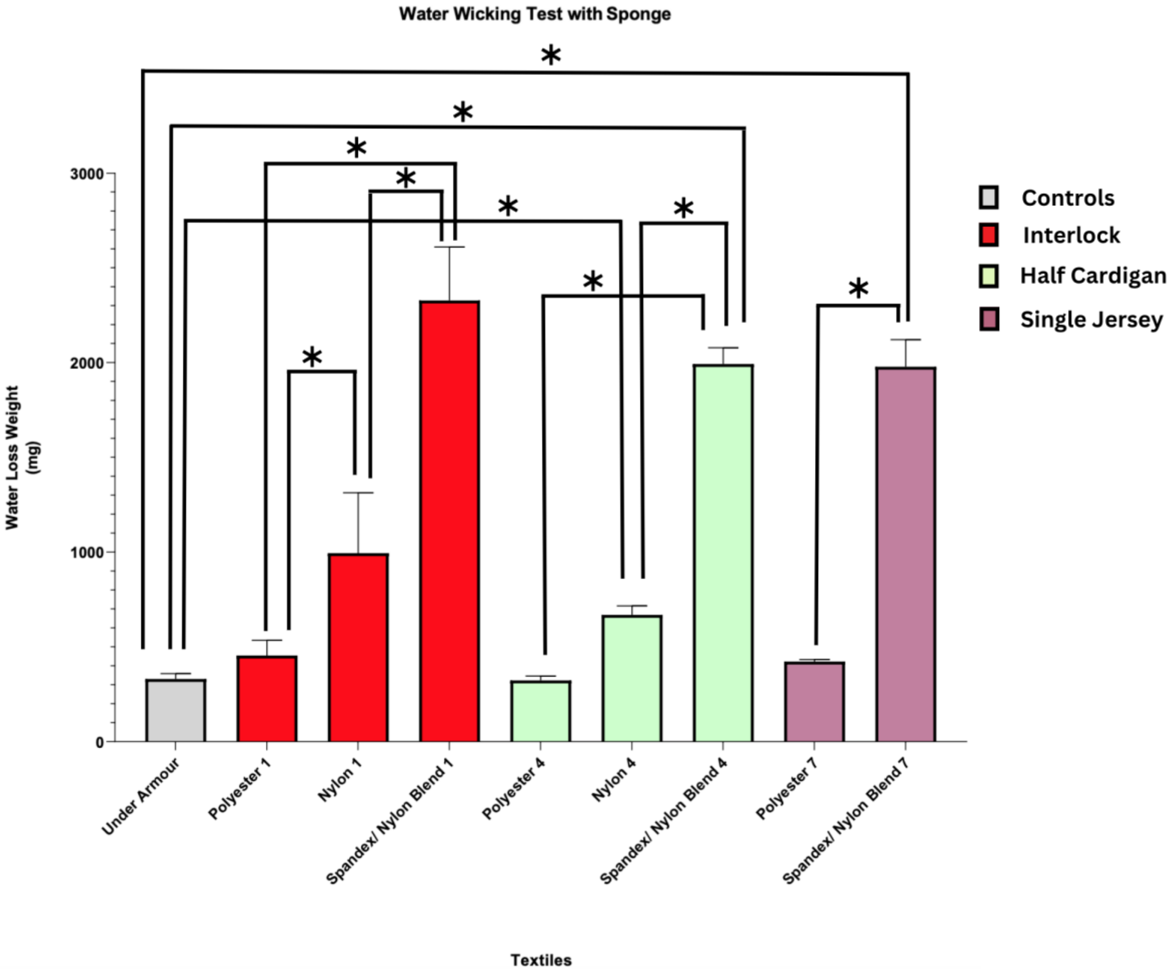


Figure 16 Water Wicking with Sponge Significant Difference. Each textile was measured in a water wicking test with sponge. The selected textiles show the increase of water loss made from our original Polyester textiles. The graphs are presented as means with standard deviations. An increase in water loss is correlated with an increase in scores. High scores are best. Asterisk (*) indicates significance where $p<0.05$.

Air Permeability Testing Reveals Which Textile has the Best Air Flow.

A test was performed to measure air permeability between 11 Textiles. The textiles are made up 9 polyester structures and 2 controls, jegging and Under Armour. This test demonstrated good air flow and breathability. Initially, the hypothesis was that the comfortable textiles would have high scores from Interlock and Single Jersey like the other experiment but, Interlock and Single Jersey scored the lowest out of all the polyesters. The second purpose of this experiment was to see if air permeability could predict mosquito bite blocking. This test turned into a great indicator on what textiles will block mosquito bites or what structures are close to blocking. This led me into the direction that Single Jersey has the potential to block with different yarn. Later, I was able to make Single Jersey with Spandex/Nylon making the textile obtain blocking capability. So, from this experiment, textiles that displayed low and middle scores were taken and enhanced with other yarns to perform well on all the other tests.

As a result of the experiment, Polyester interlock had a low score. Under Armour, Polyester interlock, and Polyester Single Jersey showed significant difference between every textile, at least $p<0.05$ (Fig 17). On this test a high score would be considered the best so, Interlock and Single Jersey showed that they had room for improvement. Although the difficulty of improving air permeability is that it creates a paradox. The paradox being highly permeability textiles are very comfortable but will not block. Abounds must be reached.

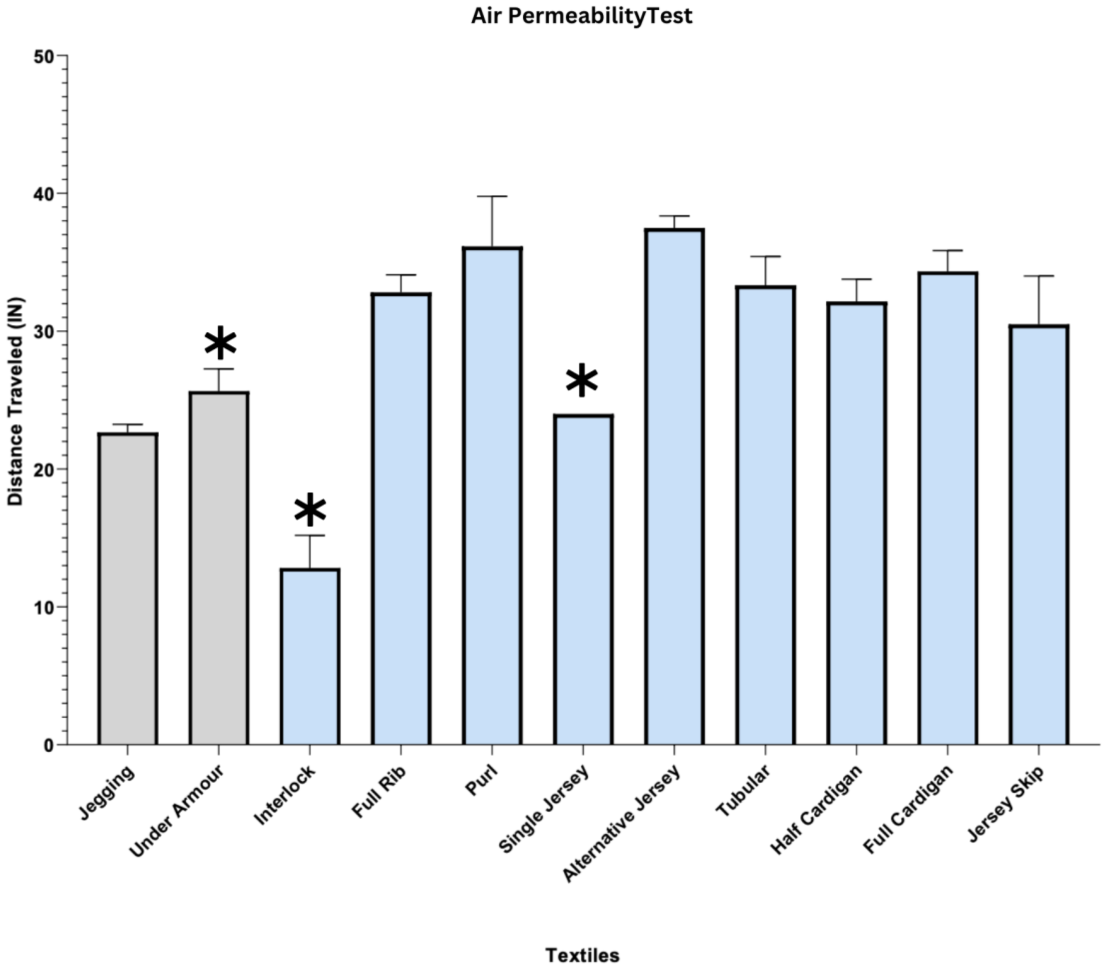


Figure 17 Air permeability Test Graph. Each textile was measured in an air permeability test. Y-axis indicates the furthest distance traveled by 20 grams of salt particles as the air passes through a textile at 100 psi. This measure is a proxy of air permeability. Each bar represents five replicates performed. The graph is presented as means with standard deviations. The higher the score, the greater the level of air permeability. Three textiles demonstrate a significant difference against all other textiles. The asterisk (*) above a bar means the textile is significant to all the other textiles by at least $p<0.05$.

2.6 Discussion

Debates on How to Measure Comfort

Understanding consumers' perceptions on comfort are essential for consumers satisfaction (Wilfing et al., 2021). Comfort can be studied and quantified. Using sensory information, a human can perceive if clothing is comfortable. The sensory information is received, processed, and then compared to expectations (Wilfing et al., 2021). We approached the question consistently with other textile studies and valued survey analysis because it is a direct reflection of consumers opinions. Physical comfort is defined as skin-clothing interaction that triggers sensory receptors that lead to a psychophysical perception. Sensations that can be triggered tacitly are smoothness, roughness, softness, stiffness, and scratchiness (Wilfing et al., 2021). Thermal, moisture, and pressure sensations can also trigger psychophysical perception (Bartels, 2005) (Bishop, 1996). This is consistent with our above definition of comfort, and this is how we measure comfort. Consumers are looking for comfort in breathability, sensory characteristics, and ease of movement (Wilfing et al., 2021). These are reasons why I chose the tests that I performed. Studies show that gender does play an overall factor in general comfort (Wilfing et al., 2021). Men prioritize thermoregulatory comfort while females prioritize sensory comfort, but these studies do not indicate that the actual perception is different, but rather the value attributed to that property. Studies also show that nationality plays a role in the interpretation of comfort. Depending where you are located can have an influence on the hand-feel of textiles (Lee et al. 2003). All our participants were US citizens. Conducting the hand-feel test personally, not a lot of variances were shown, could be due to limited nationality differences. So, an ideal product to men would be a breathable shirt that regulates temperature easily, and an ideal product for female would be a soft pair of stretchy leggings. The first product that will come from this research will be a long sleeve shirt because there is more opportunity in the male market for outdoors.

The most popular way to measure physical comfort is by a survey consisted of characteristics such as the hand feel test that was demonstrated (Stevens, et al., 2025) (Sztandera et al., 2012). Some of the descriptive words could be measured individually by other machines and methods such as measuring thickness. There are actual measurements that can be obtained like thickness, but the overall perception is measured by surveys. And the perception is more important because it dictates what a consumer will buy. This survey might be best for products geared towards certain regions instead of overall locations.

Temperature of textiles can be measured in multiple different way. One can measure the heat transfer of a textile by empirical equations. The definition of heat transfer is the prediction of the thermal resistance of fabrics (Bhattacharjee et al., 2009). This is not a method used in this research because the temperature difference is more useful to our goal of selling a product, than the thermal resistance of the fabrics per se; though in future studies both should be measured and compared. Another temperature method is measuring how hot a textile can get from a sweating hot plate (Romeli et al., 2013). A temperature difference test is ran measuring the temperature of a bare arm before a controlled incubated room and a temperature after wearing a sleeve in the controlled room. This experiment method felt appropriate to be used in finding bare arm heat gain.

Water wicking is the amount of water that is evaporated through a textile. Water wicking can be tested by water traveling up a vertical textile over a reservoir of water (Lei et al., 2020). This experiment was not used because this is measuring the travel of water along a textile and not the measurement of water being loss. Two methods were used in this research, one without a sponge and one with a soaked sponged. The one without a sponge is measuring water that evaporates off the surface of the textile and the other involving the submerged sponge measuring the water loss from the sponge through the textile. With these two methods, a total water loss by evaporation can be found.

Air flow can be measured by a machine that forces water at a given force upward through the textile (Kiron et al., 2021). This method was not used for air permeability because we were wanting to use an actual experiment that used air and not water. The method that was used was an experiment that blew air through the sample textile that pushed salt away over a given distance. This experiment ended up being an indicator on what textiles are capable of blocking mosquito bites.

Discussion of Data Specifics

The hand feel comfort test aimed to create a mosquito-blocking textile as comfortable as a well-known Under Armour textile (which does not block mosquito bites). The data demonstrates that the concept of "hand feel and comfort testing" can be supported by human intuition because in nearly all measures of comfort individuals picked a consistent fiber blend with minimal standard deviation. Changing yarn composition in similar knitted structures produced more comfortable textiles that showed statistical significance in comparison to before. A low score on this test means a high score in comfort. Spandex/ Nylon textiles and Under Armour had the lowest scores making them the most comfortable textiles. All 4 of these textiles do not share a signific difference between each other which is considered a good thing. That means during this experiment I have accomplished my goal of creating a textile that is just as comfortable as Under Armour but has the mosquito blocking capability.

My hypothesis was that the textiles that did well on the comfort hand feel test will have low heat gain scores. The lower the score the best maintainer of cooling the body off in the incubated room. A small amount of spandex caused heat gain unless it was mixed with nylon. This could be due to the air spaces being more closed off and not releasing heat. Mixing Nylon and Spandex still had closed off pathways, but the nylon acted like a more breathable fabric allowing the heat to travel through the fibers. Not having a significant difference can also be a good thing because we were trying to mimic the property of cooling Under Armour has to offer. Our objective is to recreate Under Armour but in a blocking textile form. According to my data and stats that was accomplished.

Between the two water wicking methods there were similar results other than tubulars results. Under Armours claims to be fast wicking and drying, but their scores do not show that. My hypothesis was that the most comfortable textiles from the other experiments would be the ones that dry and wick the fastest. My data and stats show my hypothesis was right. The Spandex/ Nylon textiles wicked away almost all the water within the 30-minute time duration. The reason for the two different experiments was to have the sponge work as a sweaty arm and to see if some textiles had a hard time evaporating water from one side to the other side. One textile did struggle in this method due to its structure being a double layered fabric (tubular).

The air permeability results can be looked at in two different ways. One way, when the salt travels far it indicates that the textile has good air flow, and the fabric is considered breathable. Second, the test is a good predicter if a textile is going to block mosquito bites or not.

So genuinely speaking, low and middle level scores have blocking potential. In the experiment only polyester and two controls were measured. Interlock is a blocking textile and Single Jersey blocks when using Spandex/Nylon. Interlock and Single Jersey were the two textiles that scored poorly on the air permeability test. Although I expected high comfort score textiles to score highly on-air permeability, it has led me in a different direction by predicting that changing a yarn of a medium score textile could block mosquito bites.

Final Comments on the Experimental Designs

All experiments were useful in measuring comfort and the measurements taken led us to engineer better textiles that have more market value. The most valued comfort parameters depend on gender because males more highly rate clothes that maintain temperature regulation while females are okay with sacrificing air flow and cooling properties to achieve maximum sensory comfort (Wilfing et al., 2021). The research of all the combined experiments show that no sacrifices would have to be made because Spandex/Nylon Interlock or Spandex/Nylon Single Jersey scored the highest in all experiment used. No significant difference was made between the two, but Spandex/Nylon Interlock had a higher blocking percentage when compared to Spandex/Nylon Single Jersey making Spandex/Nylon Interlock the overall best and most comfortable textile for a shirt.

Problems and Future Work

Due to the limitations discussed above, other methodologies might be incorporated to enhance or provide clarification to data in this thesis. One limitation on the hand feel survey is that we tested a specific market, in future studies one would test multiple markets in multiple regions to ensure overall comfort in multiple populations is achieved. In future work researchers could use a sweating guarded hot plate to measure (ASTM) F1868 Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials (*Guarded sweating hot plate instrumentation,* 2022). ASTM F1868 is a standard test method for thermal evaporative resistance of textiles using a guarded sweating hot plate, the machine simulates heat and mass transfer that would occur on human skin (Ding et al., 2023). Textiles could also be sent out to a facility to be tested on a sweating manikin to calculate the capability of water wicking (*Sweating manikin tests,* 2022*)*. Textiles might also be tested for air flow by an air permeability tester FX3300-IV (Kiron et al., 2021).

After these experiment researchers could compare the results with the data found in this thesis. A hypothesis is that researchers would see similar results between the methods contained here and would therefore replicate these results. As a counter argument to the suggested alternative methods, it is our hypothesis that these data would actually be less informative and pertinent to consumer decision making at the actual store. Although, the data would be interesting to compare. More research is needed.

Final Take Homes

In the hand feel comfort test volunteers preferred Spandex/Nylon textiles over Polyester, Recycled Spandex, Spandex, or Nylon. The data from the hand feel test is supported by human intuition. The major take home from the 9-factor comfort analysis is that of the individuals surveyed, they clearly preferred one specific textile fiber over all the others, the Spandex/Nylon. Thus, using Spandex/Nylon blends to construct mosquito bite blocking textiles yields most comfortable garments.

The temperature difference test calculated which textiles entrapped the most heat for the duration of an experiment. The structures Interlock, Half-Cardigan, and Jersey Skip were able to maintain a low body temperature no matter what yarn was being used. No significant difference was found between 3 structures in comparison to Under Armour. Thus, no textiles caused more temperature gain than Under Armour. The final engineered textiles were able to mimic a fabric that keeps humans cool, like Under Armour.

From the water wicking data one can conclude that neither Spandex nor Nylon independently improved water wicking from the original Polyester structures. Yet, the combination of the two created a synergic effect improving the water wicking ability. These results again support the conclusion that Spandex/Nylon blends have the most inherent comfort.

The air permeability test demonstrated that Polyester Interlock and Polyester Jersey Skip had poor air flow. Thus, blocking textiles often become less permeable as gaps are closed. This makes comfort engineering difficult. On the other hand, the air permeability test is a great indicator on what textiles might block mosquito bites or get close. This discovery lead be into the direction to add the Spandex/Nylon to jersey skip to increase its blocking ability from 7% blocking to 95 % blocking.

As mentioned, our research did uncover new combinations that converted two knits from non-blockers to blocking. These knits were Half-Cardigan and Single Jersey with Spandex/Nylon additions. The Polyester Half -Cardigan was reengineered from a blocking capability of 11.67% to an 88% blocking textile with Spandex/Nylon. The Polyester Jersey Skip was reengineered from a blocking capability of 7% to a 95% blocking textile with Spandex/Nylon. The original Polyester Interlock was blocking 92% of bites but was enhance with the addition of Spandex/Nylon to block 100% mosquito bites. In conclusion the different combination of yarns created more comfortable textiles that blocked mosquito bites. So, the ideal product made by this research would be a white long sleeve shirt made up of Spandex/Nylon interlock.

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