THE APPLICATION OF TEMPERATURE SENSORS INTO FABRIC SUBSTRATES

by

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B.S., Clemson University, 2009

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Apparel, Textiles, and Interior Design
College of Human Ecology

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2011

Approved by:

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Abstract

With continuing advancements in the area of electronics, there are more ways in which they are utilized in order to improve the lives of humans. These advancements have to led to the incorporation of electronic components into fabric structures, creating electronic textiles (e-textiles). As it has become possible to place small electrical components within clothing without the performance of the electronics being hampered, research has been conducted in the use of e-textiles in measuring aspects of the human body, such as the heart rate and perspiration rate. In the area of skin temperature, research has been conducted in the past using e-textiles for skin temperature measurement, but past efforts have been unsuccessful in incorporating useable temperature sensors into a fabric substrate. This study compared three types of sensors incorporated into woven and knitted fabrics, using insulated thermocouples, un-insulated thermocouples, and resistance temperature directors (RTDs). Three incorporation methods (weaving, interlacing into knit, and stitching) were used in six fabric samples, with the three sensor types woven and stitched into three woven fabric samples, while the sensors were interlaced into knitted fabric and stitched into the three knitted samples. Fabric hand washing and temperature measurement tests were conducted, and the temperature readings were analyzed statistically for comparison. The analysis conducted showed that the thermocouples that were interlaced or stitched onto the knitted fabric samples were best for temperature measurement due to their accuracy and durability, while the RTDs were unusable as a temperature sensor, as the removal of the electrical connectors during washing eliminated the calibration that was established before washing. This research was supported in part by the Institute for Environmental Research at Kansas State University.

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Acknowledgements

There are several people, who without their help it would have been impossible for me to conduct this study. In terms of the sample preparation, I am forever in debt to George Eads and Susan Linn, as it would have been impossible to me to weave and knit my fabric samples without their guidance. Thanks must also go out to Eric Waters, Luke Schooler, and Steve Eckels from IER, as I would have not been able to obtain temperature sensors and determine how to obtain measurements, as well as devising a process to calibrate and test the fabric samples for temperature measurement. I must also thank Dr. Diana Sindicich, Dr. Elizabeth McCullough, and Dr. Sherry Haar for serving on my committee, as they have graciously donated their time and wisdom in order to ensure that the research that has been conducted will be pertinent and a useful expansion of knowledge in the area of textile science. Last, and not least, I must thank my friends and family for their wisdom and guidance, as it would have been impossible for me to both accomplish everything this far in life, as well as keep my sanity at the same time.

CHAPTER 1 - Introduction

Background Information

Thermoregulation is essential for humans, as it would be impossible to survive if the human body was unable to adjust to changes in the surrounding environment. For instance, whenever the human body is generating unnecessary heat, blood vessels widen and sweating occurs, while additional heat can be created by shivering (Charkoudian, 2003). For a human, one of the most harmful conditions is when the body's natural regulation mechanisms are unable to normalize the body's temperature, causing the body to reach temperature extremes and causing injury to the body. At low core body temperatures (below 35°C), hypothermia occurs, with a body temperature lower than 28°C leading to potential death (McCullough and Arora, 2004). At high core body temperatures (1°C to 4°C above normal), hyperthermia occurs when the body is unable to release unnecessary heat, with heat stroke and death occurring when the body is no longer able to cope with the extreme temperatures (Simon, 1993). An individual's tolerance level in terms of temperature is related to multiple variables, such as the physical condition of the individual and the genetics of the individual, with the tolerance level helping determine the performance of the human body. It is because of the change in performance of the human body due to body temperature that skin temperature measurement is an important area of study, with models developed in order to determine how body performance is tied to skin temperature (Pilcher, Nadler and Busch, 2002). For human skin temperature measurement, it is crucial that the testing be conducted on human participants, as subject testing allows research to be done on individuals who are performing tasks that would normally be conducted during their routine. While thermal mannequin testing would be a safer alternative, the data generated from testing on mannequins cannot take into account the performance of the individual or the demands of complex physical activities. Human subject testing has been performed in the past with skin temperature sensors that are individually glued or taped onto the skin, with wires impeding the wearer's mobility and the attachment method employed potentially causing irritation to the wearer. It is because skin temperature testing is crucial that new testing methods are in development so that the individual will not be hampered in terms of movement and comfort.

With recent advancements in electronic technology, it is possible to apply electronic sensors to the human body without hampering the performance of the subject. The decreasing size of electronics also make it possible to incorporate them within textile fabrics, with the number of uses for this technology rapidly expanding. In the area of aesthetics, the use of electronic textiles allows the fabric to become more or less pleasing to the senses, such as the ability to change color or emit light (Thiry, 2010). It is also possible to incorporate electronic components into fabrics for other technical purposes, such as being able to determine the amount of sweat a person gives off, as well as determining how quickly a wound is healing (Luprano, Sola i Carlos, Ridolfi, Pasche and Gros, 2007). Researchers have also been studying how temperature sensors could be incorporated within a garment, with fabric structures containing the more conventional metal-based thermocouples more successful than those constructed of fibers that are treated to be become thermocouples themselves (Ziegler and Frydrysiak, 2009). Several types of temperature sensors have been used to record skin and air temperatures, with each having their own advantages and drawbacks depending on the application. With more conventional methods of temperature sensing more reliable than textile-based thermocouples, the use of traditional thermal sensors such as thermocouples and resistance temperature directors (RTDs) must be examined with the eventual goal of determining what methods would be best used to incorporate thermal sensors that can be used to measure the skin temperature of the wearer at critical points on the body.

Purpose of Study

The purpose of this study was to determine the effectiveness of weaving and interlacing thermocouples and RTDs into a textile-based structure. The performance of each type of temperature sensor was then evaluated based on the ability of the sensor to measure temperature accurately, with measurements taken after incorporation and after washing the fabric samples. The goal of conducting research in this area was to develop a thermal sensing garment that would allow an individual to be able to wear a fabric garment that has temperature sensors integrated within its structure. The main application areas of this technology would be for scientific research, as this fabric will be able to measure skin temperature of the individual without hampering the range of tasks that the individual can perform. The goals of this study were to answer the following research questions:

1. a. Did insulated thermocouples accurately measure air temperature when woven into fabric, interlaced into knitted fabric, and stitched onto fabrics?

   b. Did un-insulated thermocouples accurately measure air temperature when woven into fabric, interlaced into knitted fabric, and stitched onto fabrics?

   c. Did RTDs accurately measure air temperature when woven into fabric, interlaced into knitted fabric, and stitched onto fabrics?

   d. Did RTDs accurately measure air temperature when woven into fabric, interlaced into knitted fabric, and stitched onto fabrics?
2. a. What effect did hand washing have on the ability of insulated thermocouples to measure temperature when they were washed after being integrated into fabrics?

b. What effect did hand washing have on the ability of un-insulated thermocouples to measure temperature when they were washed after being integrated into fabrics?

c. What effect did hand washing have on the ability of RTDs to measure temperature when they were washed after being integrated into fabrics?

The main reason for this research is to advance the knowledge and application of electronic components within textiles. As research has been conducted in both thermal sensing technologies and the thermal properties of textiles, there have been several methods that have been developed in order to develop a textile that is able to measure the skin temperature of the wearer without hampering the performance of the wearer themselves (Pilcher, Nadler, and Busch, 2002). However, the push to incorporate temperature sensing technologies within textiles in the past has met difficulties. The methods utilized by Ziegler and Frydrysiak (2009) in the treatment of fibers to become temperature sensors themselves have been less than successful. While this eliminates the need for wiring within the fabric structure, the resulting fabric generates a low voltage, requiring a very sensitive recording instrument was needed in order to use the fabric accurately (Ziegler and Frydrysiak, 2009). This study was conducted because methods utilized to make temperature sensing fabrics were not effective in terms of generating a consistent temperature measurement device in the past. The aim for this research was to determine what methods and sensor types would be best utilized once integrated within a woven or knitted structure while ensuring that the temperature sensors were able to perform accurately and consistently.

The main audiences for this study are those who work in the area of electronic textiles research, as well as those who conduct research on skin temperature measurements and human performance.

Methods

To construct both the woven and knit fabric samples, a 100% 10/2 cotton yarn was used in order to maintain consistency throughout sample construction. The thermocouple that was chosen for implementation within the fabrics was a 30 gauge Type T thermocouple, with one set of thermocouples having an insulated coating surrounding both of the wires, while another set of thermocouples of the same type have had the insulative coating removed, separating the wires. In order to incorporate an RTD into a fabric structure, a 1.1 meter section of 30 gauge copper was used in order to create a single RTD. To incorporate the thermocouples (both insulated and un-insulated) and RTDs into the three woven fabric samples, one of each sensor type was woven into the samples, while the other was stitched onto the woven fabric. The thermal sensors were placed within the three knit fabrics with one of each sensor type being interlaced into knitted fabric samples, while the other sensors were stitched onto the fabric surface. After the sensors were placed within the fabrics and calibrated, they experienced multiple hand washings, following the hand washing and drip drying methods established in AATCC Test Method 124-1996 "Appearance of Fabrics after Repeated Home Laundering", with all sensors tested for accuracy of temperature measurement after 1, 3, 5, 10, and 20 hand washes.

For this research the independent variables were:

- Thermal sensor type used
    - Insulated thermocouples
    - Un-Insulated thermocouples
    - Copper RTDs
- Method of applying sensor into fabric sample
    - Weaving

  - Interlacing in knitted fabric
  - Sewing onto fabric sample surface
- Number of launderings
  - new unlaundered samples
  - samples that have been laundered 20 times

while the dependent variables were:

- Breakage of sensors
- Accuracy of sensors

CHAPTER 2 - Literature Review

Thermoregulation and Human Body Temperature

Human Thermoregulation

Thermoregulation is the process by which the human body makes suitable changes to either dissipate unnecessary heat from the body through either widening of blood vessels (cutaneous vasodilation) and sweating, or generate additional heat through shivering and the narrowing of the blood vessels (cutaneous vasoconstriction) (Charkoudian, 2003). There are various parts of the human body that operate in the constant monitoring and altering of the body temperature, as certain conditions will make it necessary for the body to alter its temperature in order to maintain normal functioning. This process requires many parts and conditions to operate, and in J. Werner's research in 1980, the body receives information from the outside environment (effectors) which is sent to the passive system of the thermoregulatory process, which consists of skin, fat, muscles and viscera. Each passive system (with the exception of fat) has a set of receptors that determine a temperature change has just occurred, prompting electronic signals to be sent to the brain through the spinal cord into the controller portion of thermoregulation, which determines what actions must be done by the body to maintain a healthy body temperature. The spinal cord then sends and receives signals from the other parts of the brain to determine what actions must be taken in order to maintain thermoregulation. Both the spinal cord and the cortex then send messages to the body to make changes in order to maintain a constant body temperature. The cortex alters the human behavior by going indoors when in a cold environment, or the spinal cord signals the sweat glands to dissipate additional heat that is being generated by the body in warm environments (Werner, 1980). In this process, it is the spinal cord that is key in maintaining thermoregulation, as it allows the brain to communicate with the rest of the body to ensure survival when changes in the environment are encountered.

As the human body is constantly generating heat through various metabolic processes, the metabolism of humans must be considered when analyzing human thermoregulation, according to N. Charkoudian's research in 2003. The body's resting metabolic rate of heat production is between 80 and 90 kcal/hr, and when heat generation is more or less than the resting range the body will correct itself to dissipate more heat into the environment or generate more heat internally. Cutaneous vasodilation operates by widening the blood vessels, allowing for more heat to be directed towards the skin as opposed to within the body, causing increased cardiac activity in order to shift the blood flow in the body. Working in tandem with the cutaneous vasodilation, the evaporation of perspiration decreases the skin temperature, operating until equilibrium is reached where heat dissipation equals the heat generation of a body. In terms of colder environments, blood vessels will constrict (cutaneous vasoconstriction) in order to reduce the amount of heat that is being transferred convectively through the skin (Charkoudian, 2003). Additional heat generation in the body is initiated by shivering, caused by muscular contractions in order to generate movement by the body to cause the body to produce more heat. Charkoudian’s research indicates that messages that are sent between the various parts of the body and the brain in order to either release or generate additional body temperature It is through these processes that a human is able to maintain thermoregulation, as the process aims to either release surplus heat that is generated through metabolic processes or generate more body heat than is normally produced in metabolic processes.

The Measurement and Models of Thermoregulation

According to the standard put forth by the International Organization for Standardization (ISO), there are several methods in evaluating thermal comfort and strain placed upon the body, of which skin temperature measurement is one method. In order to determine a mean skin temperature (t_{sk}) of an individual, up to 14 measurement points (t_{ski}) in different regions of the body can be utilized in order to obtain a temperature that is indicative of the whole body, with the use of fewer points possible based on the conditions of testing. (ISO 9886, 2004). The 14 temperature points are measured with the use of temperature sensors placed in contact with the body with the measurements weighted based on the number of points used during testing , with the weighting shown in Table 2.1. The data that is generated will then be entered into the equation $t_{sk} = \sum k_i \; t_{ski}$ to obtain the mean skin temperature (ISO 9886, 2004).

Table 2.1: Measuring Sites and Weighting Coefficients of Mean Skin Temperature (ISO 9886, 2004)

Skin Temperature Point	Site	4 Points	8 Points	14 Points
1	Forehead		.07	1/14
2	Neck	.28		1/14
3	Right Scapula	.28	.175	1/14
4	Left Upper Chest		.175	1/14
5	Right Arm in Upper Location		.07	1/14
6	Left Arm in Lower Location		.07	1/14
7	Left Hand	.16	.05	1/14
8	Right Abdomen			1/14
9	Left Paravertebral			1/14
10	Right Anterior Thigh		.19	1/14
11	Left Posterior Thigh			1/14
12	Right Shin	.28		1/14
13	Left Calf		.2	1/14
14	Right Instep			1/14

There are situations in which it will be impossible for a human to make thermoregulatory changes in order to maintain a constant 37ºC body temperature. Whenever this type of situation occurs, the performance of the body will change due to the various effects that temperature has upon the body. While advancements in technology have made it less likely for humans to encounter these extreme environments on a daily basis, there are certain situations where it is unavoidable, such as when military operations are being conducted or where a job is being performed that requires the worker to expose themselves to the elements. In order to determine how the body will perform when exposed to hot and cold environments, models have been created based off of several parameters measured from the human body. In their research in 1987, R. Haslam and K. Parsons studied four differing models: the Giovanni and Goldman, the ISO/DIS 7933 model, the J.B. Pierce Lab (2-node) Model of Human Thermoregulation, and the Stolwijk and Hardy 25-Node of Human Thermoregulation. For both types of environments, the key measurements used by the four studied models include the air temperature, air speed, humidity, and the metabolic rate. However, each model also takes into account other parameters that may make one model more suitable than the others in given situations. For instance, the Giovanni and Goldman model emphasizes internal body temperature measurements, as the equations that are used to derive human performance are based off of rectal temperature measurements in hot environments for both clothed and unclothed humans. The ISO/DIS 7933 body model places more of an emphasis on the evaporative cooling of the human body, as the sweating and evaporation rates are key variables in this model to examine human performance in hot environments for both clothed and unclothed humans. In terms of the J.B. Pierce Lab (2-node) Model of Human Thermoregulation, the use of heat transfer due to blood flow between the skin and the interior of the body makes it the most versatile of the models examined in their study, as it is able to predict human performance in either hot or cold environments for both clothed and unclothed humans. As for the Stolwijk and Hardy 25-Node of Human

Thermoregulation, it uses spherical/cylindrical measurements of six segments of the body which consist of 4 layers, with the blood acting as the last segment in the body, but can only predict human performance in hot/cold environments for unclothed humans. It is with the use of these models that it is then possible to make an educated determination on how a body will perform in a given set of environmental conditions.

While models can be used in some circumstances to predict human performance, there will be times in which meta-analysis will be the only way possible to determine in what ways human performance will be altered due to environmental changes. Pilcher, Nadler and Busch performed a meta-analysis of 226 previous studies that have been conducted on the human body performance under both hot and cold conditions based on previous experiments of others, for which any temperature above 21.1ºC is considered a hot temperature and below 18.3ºC a cold temperature. The temperatures used in the 226 previous studies were then translated using the Web Bulb Globe Temperature Index (WBGT) to allow comparison between studies. The data were then analyzed, taking into account the temperature of the study, the duration of the test, the preparation of the participants, and the type of task that was required of the respondents in each study (Pilcher, Nadler and Busch, 2002). One main finding of the meta analysis was that changes in performance are most drastic at the extreme high (≥32.2ºC) and low (≤10ºC) temperature readings, as the human body is not accustomed in operating in extreme environments. As for comparisons between hot and cold temperature and human performance, on average humans perform better in warmer environments than in colder environments, as performance decreased more rapidly when environmental temperature decreases (Pilcher, Nadler, and Busch, 2002). The amount of time in which a human is subjected to extreme environments is also crucial, as shorter experiments had a more extreme negative effect on the body in comparison to longer experiment runs, with a possible explanation for this outcome being that the human body will be able to acclimate to a given environmental situation as long as it does not approach a lethal extreme.

The Human Body and its Reaction to Cold Environments

Colder environments have a negative effect on the performace of humans, with the possibility of the environment making it impossible for the body to maintain a constant body temperature through thermoregulation, causing hypothermia. There are various causes that lead to hypothermia related to mechanisms used in the thermoregulation of the body, with the mechanisms that lead to body heat loss being radiation, conduction, convection, evaporation, and respiration (McCullough and Arora, 2004). Radiation occurs when body heat rapidly exits the body from non-insulated parts of the body such as the head, and is the most common way to emit body heat. Conduction heat loss occurs when body heat is given off due to direct contact with another object. The loss of body heat when an individual swims occurs by conduction, dissipating their body heat in the water. The convective mechanism involves the movement of fluid or gas, such as when the wind moves the layer of heated air that surrounds the body. Convection explains how wind chill causes faster body heat loss than what would otherwise occur. Both evaporation and respiration mechanisms are heavily related, as they both involve the movement of water in and out of the body. Evaporation cools the body by releasing water through the body via respiration to vaporize (sweating). Respiration in turn cools the body by releasing heated carbon dioxide and taking in oxygen that is colder than the internal body temperature (McCullough and Arora, 2004).

Hypothermia itself goes through stages based on the body temperature of the human, with symptoms becoming more severe as the body temperature decreases. With mild hypothermia, a human has a body temperature between 32.2ºC and 35ºC, with symptoms including shivering and impaired judgment. Moderate hypothermia occurs when the body temperature is between 28ºC and 32.2ºC , with common symptoms being a decreased heart rate and hypotension. When the body temperature is lower than 28ºC, severe hypothermia occurs, leading to apnea and eventual death (McCullough and Arora, 2004). With hypothermia being a gradual process, it is impossible to a human to make changes to ensure that mild hypothermia is treated immediately in order to prevent more serious complications.

However, as shown in D. Sessler's research in 2001, there are differing guidelines present in the medical field pertaining to hypothermia, as some practitioners classify mild hypothermia as a condition where the human body is between 34ºC and 36ºC, with most of these cases being non-fatal (Sessler, 2001). As human body temperature falls to within the mild hypothermia range, changes occur within the human body, as it will lead to an onset of thermoregulatory vasoconstriction, which is the narrowing of the blood vessels in the human body. Vasoconstriction significantly decreases subcutaneous oxygen tension (concentration of oxygen) in humans, which increases the chance of infection occurring in a wound area (Sessler, 2001). There are multiple medical complications that could arise due to mild hypothermia, such as increased blood loss and wound infection, leading to a longer hospital stay for the average patient and increasing health risks and costs.

While cases of mild hypothermia are more common, it is the cases of severe hypothermia that will attract the most medical attention, as it is these cases that are most likely to cause more serious medical complications and possibly death. The Centers for Disease Control and Prevention (CDC) in the United States has developed guidelines in order to take measures in preventing hypothermia and frost bite in extreme cold temperatures. The CDC classifies extreme cold weather as "...a dangerous situation that can bring on health emergencies in susceptible people, such as those without shelter or who are stranded, or who live in a home that is poorly insulated or without heat" (Centers for Disease Control, 2007). The elderly and infants are more susceptible to the bodily harm that could be done due to extreme cold weather, as the elderly cannot generate body heat as fast as other humans, and infants lose body heat faster than other humans and cannot generate body heat by shivering. Several measures that are put forth by the organization include wearing properly insulative clothing and to avoid exerting the body in cold environments, as the body persipiring will lead to more of a strain on the human body.

The Human Body and its Reaction to Warm Environments

While colder environments can be detrimental to human performance, extreme heat and hot environments can also have a drastically negative effect on the human body. According to H. Simon, the average body temperature of a human being is 37ºC, normally starting out at a base of 36ºC in the morning, eventually reaching a peak of 37.5ºC in the late afternoon, after which the body temperature will decrease gradually in response to the environmental changes that occur when the sun sets (1993). However, the condition of hyperthermia occurs whenever the body temperature is at least 1ºC to 4ºC higher than normal, as the human body is producing more heat than it is able to dissipate. During hyperthermia the effects can be drastic, as the heart beat of the average individual will increase 8.5 beats per minute for each 1ºC increase during an infection, but those with heart disease may encounter ischemia, arrhythmias, hypotension, and even congestive heart failure (Simon, 1993).

However, while the temperature in a given environment plays a crucial role in determining the body temperature of an individual, there are times where other factors will become evident according to Saper (1994). In terms of the various illnesses that increase body temperature, the most common of these is fever, which is the blanket term for any medical complication that causes the body temperature of an individual to increase at least 1°C to 4°C (Saper, 1994). The symptoms caused by fever are due to a reaction by the immune system in a body, during which the body performs the same actions that would be used to maintain a normal body heat in a colder environment, while in this case it leads to an elevated body heat. During a fever, the body will begin to increase production and secretion of various metabolic products, and the brain will then send messages to the rest of the body to ensure those actions such as shivering and the increase of blood pressure and pulse is performed in order to maintain the elevated body heat. These actions may cause certain individuals to perform in ways that they would not normally act, such as entering a state of malaise (a feeling of illness/uneasiness), feeling constant drowsiness, and anorexic symptoms (loss of appetite) (Saper, 1994).

While humans are able to adapt to colder environments by adding more layers of clothing to prevent hypothermia, hot climates present a different problem with respect to the prevention of hyperthermia. According to Hajat, O'Connor and Kosatsky (2010), when temperatures are increased, the chances of heat stroke increase, with 15% of all recorded heat stroke cases proving fatal even when medical care is provided promptly. The authors were also able to find several differences in the medical complications that arose during heat waves in Europe and the United States, as increases in complications due to respiratory diseases were more common in Europe, while in the US heart disease, acute myocardial infarction, and congestive heart failure were more common health complications to occur in heat waves. However, instances of renal disease, diabetes and mental disorders increase during heat waves in the US, Europe and Australia (Hajat, O'Connor and Kosatsky, 2010).

Temperature Sensors

The Four Basic Thermal Sensor Types

In order to measure temperature in any situation a thermal sensor will be used. According to Kester, Bryant and Jung (2005), the four most commonly used sensors that are used to measure temperature are thermocouples, Resistance Temperature Directors (RTDs), thermistors, and silicon-based semiconductors. Each temperature sensor type inherently possesses differing characteristics and operates differently than the others, making some sensor types more or less suitable for certain situations. It is through the examination of these thermal sensor types that will determine what type of sensors can be used in the construction of a temperature-sensing textile.

Thermocouple Sensors

According to Tempsens Instruments, the German physicist Thomas Seebeck discovered the thermoelectric effect (also known as the Seebeck coefficient or thermopower), which helps serve as the basis by which thermocouples are able to record temperature (Tempsens Instruments). Thermocouples operate based upon the different charges generated when two different metals come into physical contact with each other, as well as the temperature differences of the junctions between the two metals. The temperature differences between the metal junctions generate a voltage that can be measured in order to determine the temperature at a given point (Tempsen Instruments). If there is no temperature difference between the junctions, the voltage from each junction will then cancel each other out, preventing current flow through the thermocouple. In order to operate a thermocouple, it is important that the junctions must be designed with hot and cold junctions in order to ensure temperature measurement. The hot junction is the metal junction that will be exposed to the environmental temperatures being measured, while the cold junction (reference junction) will be held at a constant known temperature in order to generate a voltage. It is when these junctions are constructed in a system that a thermocouple is created, with two conductors and a measuring junction utilized to generate a current and measure the resulting voltages (Tempsens Instruments). The resulting voltages that are generated in the thermocouple are minute, measured in millivolts (mV), forcing thermocouples to be used mainly in elevated (above 100°C) and depressed temperatures (below -50°C). However, it is possible to change the temperature ranges to be measured by utilizing appropriate equipment and varying the types of metal wires that are utilized in the thermocouple.

In applying thermocouples into the substrate of a fabric, the diameter of the metal wires should be as similar as possible to the existing yarns in order to become fully integrated. In order to match the diameter of threads used in textile production, the thermocouple wires will need to be at a high gauge. However, this integration comes at a price, as when the thermocouple wire diameter becomes smaller, the temperature extremes at which it can be used is diminished, as well as the durability of the thermocouple. This decrease in temperature sensing range is due to both the increased fragility of the thermocouples and the increased probability of the thermocouple being damaged by increased temperatures (Tempsens Instruments).

Resistance Temperature Directors

In Desmarais' research, another type of sensor that can be used to record temperature are Resistance Temperature Directors, commonly called RTDs (1996). RTDs are able to measure temperature with the use of an electrical resistor that will change the amount of resistance generated based on temperature (Desmarais, 1996). The sensing instrument is constructed with either a wire coil or a conductive film grid, which is then packaged so it can be placed within a structure to measure temperature. The material that is used in the construction of the RTD sensor will set limits on the temperature ranges at which testing can be conducted. For instance, platinum RTDs can measure temperatures in the range of -267.8°C to 648.9°C, while copper RTDs are able to make temperature measurements in the -73.3°C to 148.9°C range (Desmarais, 1996). It is also important to make sure that the wires that are used to transfer the information to the recording instrument are insulated correctly, as the insulation may melt under higher temperatures. For instance, nickel-plated copper wires that are insulated with TFE Teflon are able to be used to temperatures up to 260°C, while nickel-plated copper wires that are insulated with fiberglass are able to be used to measure temperatures up to 482.2°C (Desmarais, 1996). The insulation also helps with generating accurate data, as the resistance encountered on a wire will change if it comes into contact with another wire, while the insulation prevents any contact with the wire.

Thermistor Sensors

According to Analog, thermistors are also another viable option in temperature sensing devices. Thermistors are constructed like RTDs, made from semiconductive material that can exhibit a negative or positive temperature coefficient. Negative temperature coefficient materials are mostly used for thermistors, as a thermistor is a resistor whose resistance will change based upon the temperature of a given environment (Analog, 2010). However, the main difference between a RTD and a thermistor is that while a RTD is made from pure metal, a thermistor can be made from a ceramic or a polymer. It is this material composition difference that helps make thermistors a viable option, as it is by far the most sensitive to temperature change when compared to the other temperature sensors. This resistance change can be used to measure temperature, as a reference voltage will be taken in order to determine how much electrical resistance will occur at a higher or lower temperature. In order to record the voltage, an operational amplifier (Op Amp) is used to increase the amount of voltage in order to ensure that an output can be determined by an analog to digital converter (Netrino, 2009).

Silicon-based Semiconductors

In the comparison research of Kester, Bryant and Jung (2005), as well as Baker (2002), it was found that the application of silicon-based semiconductors that are temperature sensor provides an alternate way to measure temperature in certain conditions. The semiconductor sensor operates based on installation within an integrated circuit (chip), which operates through the regulation of how much voltage is sent through the diodes and transistors in the circuit. The voltage of semiconductors is regulated through the transfer of electrons through the crystalline structure of the semiconductive material (Kester, Bryant and Jung, 2005). The semiconductor-based temperature sensor takes advantage of the difference between the voltage being emitted through the semiconductor and the current that is flowing through the system (Kester, Bryant and Jung, 2005). The voltage can then be converted by the microprocessor into a reading that can be measured, and provide a temperature reading (Baker, 2002).

Advantages and Disadvantages for Each Thermal Sensor Category

Each type of temperature sensor possesses different strengths and weaknesses, making them suitable for some situations and useless in other situations. In order to determine what type of temperature sensor would be best for the implementation within textiles, these strengths and weaknesses must be examined.

A strength of thermocouples is the varying size at which thermocouples can be made, which is necessary when implementing the sensor into a textile. This size range makes is possible to have a thermocouple that is similar in size to the fibers within the woven fabric. Other strengths of thermocouples include the low costs of materials and construction of the sensor, as well as the fact that thermocouples can be used in the most varied of environments (Tempsens Instruments). However, one of the main weaknesses of thermocouples is that they are more prone to errors when the ambient temperature changes, making it necessary for calibration to be performed when the temperature has changed significantly. The low voltage output also requires that the machinery that reads the output be very sensitive to voltage changes (Baker, 2002).

Reliability and accuracy are two of RTDs biggest strengths, as experiments can be repeated multiple times with RTDs and the results will remain similar over time. Most RTDs types are interchangeable and will have much less testing error in comparison to thermocouples. For instance, at 204.4°C a 100 Ohm DIN, Grade B platinum RTD will have a standard error of ± 1.2°C, while a Type K thermocouple will have a standard error of ±2.2°C (Desmarais, 1996). However, the reliability comes at a price, as the materials used in the production of RTDs and the construction can cost 4 to 10 times more than a thermocouple. RTDs are also less useful in terms of fragility, as they are more likely to break when placed under stress in comparison to thermocouples (Desmarais, 1996).

The one advantage to using a silicon-based temperature sensor is the simple fact that it can easily be implemented in any integrated circuit. This allows the circuit to complete multiple tasks as well as measuring temperature, decreasing the amount of interference caused by a temperature sensor (Baker, 2002). However, there are major disadvantages to using silicon-based sensors, one of which is the lack of accuracy in comparison to other temperature sensor types, as in Baker’s research it was found that while a thermocouple commonly has variation of ±0.5°C, the variation observed in the silicon-based sensors is ±1°C (Baker, 2002). The other disadvantage of silicon-based temperature sensors is the diminished temperature at which measurements can be made, as the temperature range at which measurements can be made is between -55°C to 150°C, which pales in comparison to other temperature sensor types (Baker, 2002). It is because of these advantages and limitations that silicon-based temperature sensors are used in mainly electronics.

As for thermistors, they share many of the advantages and disadvantages with RTDs in terms of the construction, but differ widely on cost, as thermistors for the most part are comparable in price to thermocouples. The increased accuracy that is created through using polymer/ceramic material also creates a great advantage, as thermistors are the most sensitive of all the thermal sensors, able to obtain the most accurate of readings (Analog, 2010). However, the fact that thermistors are the most sensitive also creates a major disadvantage, as one of these sensors will only able to record temperatures in much smaller range in comparison to the other sensors. While thermistors can be used at temperatures between -100°C to 450°C, one sensor by itself will only be able to cover a fraction of this range (Baker, 2002). If this limit is ignored, it is highly likely that the sensor may be damaged or give off erroneous measurements due to the extreme temperatures that it encounters (Analog, 2010).

When implementing a thermal sensor into a fabric, it will be necessary for the sensor to be similar in size to the fibers, be relatively low in cost, be used in varying environments, and be able to record accurate measurements. It is because of these required specifications that thermocouples and RTDs will both be used in this study, as they are both available in sizes needed to be incorporated into the fabric, are cost effective for textile implementation, and have the ability to record temperatures and maintain consistency much better in comparison to the other sensors.

Electronic Textiles and Their Applications

The Application and Wearing of Electronic Textiles

When electronic devices are embedded within a textile structure, an electronic textile (e-textile) is created. E-textiles (also known as smart clothing) allow clothing worn on a regular basis to utilize technological advancements, developing wearable technology (Thiry, 2010). In some e-textiles, the usage of the electronics serves mostly as an aesthetic aspect, such as creating fabrics that can light up or become a portable MP3 player. However, some researchers are more interested in the utilitarian aspect of e-textiles, as it is possible to use electronics embedded within textiles to perform tasks such as making biochemical and bioelectrical measurements of the wearer's body performance (Luprano, Sola i Carlos, Ridolfi, Pasche and Gros, 2007). It is with the development of technology that more types of electronics can be utilized in the everyday life of the average person, whether it be for the aesthetics or the utilitarian approach.

The work of Lin and Tang for NASA's Jet Propulsion Laboratory in 2000 examined the crucial ability of an electronic component within the e-textile be able to withstand the normal conditions that occur to the wearer in a given garment. In their research, Lin and Tang studied the implementation of self adhesive sensor patches for biotelemetric readings (heart rate, blood pressure, body temperature, etc.) within flight suits for the astronauts. The sensors were 3cm by 3cm in size, and were integrated with microelectromechanical sensors, allowing data to be processed and transmitted through the use of radio signals (Lin and Tang, 2000). In order to power the sensor, a circuit built into the chip would extract power from the incident radio beam that occurs when the sensor transmits its data, and a handheld radio transceiver would need to be placed close to the sensor in order for data transmission to occur (Lin and Tang, 2000).

In order to ensure that e-textiles are flexible enough to be worn, Vatanparast, Hashizume, Kitaura, and Mori conducted research in 2007 on making the electronics placed in textiles as small and non-obstructive as possible without harming the performance of the garment. The concept of non-intrusive wearable sensors relies heavily upon the small size of the electronic being placed within a particular piece, with several sensors being placed in clothing articles that communicate information to a device such as a cell phone or PDA (Vatanparast, Hashizume, Kitaura, and Mori, 2007). The sensors could be placed in items such as watches and necklaces, with implementation within clothing in the distant future. Their sensors were similar in size to 5 quarters stacked together and contained multiple types of sensors that could record different types of data, such as a heart rate and skin temperature (Vatanparast, Hashizume, Kitaura, and Mori, 2007). While these sensors currently would not be able to be placed in any garment due to lack of flexibility, the researchers hope to alter the material used in constructing the sensors in order to increase the amount of flexibility inherent in the device. The data was then communicated wirelessly to a device that could collect and process it (Vatanparast, Hashizume, Kitaura, and Mori, 2007).

Aesthetics and Use of Electronics in Textiles

In the area of e-textiles, many researchers have decided to emphasize the use of the enhanced aesthetics in order to provide a more pleasing garment. The use of lighting and color changing fabric has become a very important aspect in e-textiles, according to Thiry (2010). While some may not consider these a serious application of this sort of technology, the added enjoyment and fun of wearing a more fashionable product provides satisfaction to both the wearer and those looking on (Thiry, 2010). Because most of these color-changing e-textiles are made mostly for novelty, their price is more important than the successful integration of the technology itself. It is hoped that through the expanded usage of these types of garments that the public will be more educated on the useful aspects of e-textiles, potentially increasing the market for utilitarian e-textiles (Thiry, 2010). Thiry also mentions that it is important that the non-utilitarian aspects be researched as well, as it is while using those types of fabrics that individuals can think of the electronic aspect of the fabric as more of an accessory than the fabric merely being the platform for the electronic functions.

According to Webe, Glaser, Jung, Lauterbach, Stromberg and Sturm in 2003, the increased usage of electronics will only increase the demand of e-textiles, as they will be able to provide a greater array of interfaces to be used. This growth in the area of e-textiles is largely due to both the decreasing cost of the microelectric components that are used in the production of e-textile fabrics as well as the maturation of various technologies that allow this synthesis of electronics and textiles possible (Webe, Glaser, Jung, Lauterbach, Stromberg and Sturm, 2003). One technology that is taking advantage of the increased use of e-textiles is interconnecting and packaging technology. For example, the integration of a speech-controlled MP3-player into a sports jacket is made possible through the use of copper wires that are coated with silver and polyester fibers, a printed circuit board, a rechargeable lithium-ion battery, a MultiMediaCard for memory storage and a capacitive keyboard module (Webe, Glaser, Jung, Lauterbach, Stromberg and Sturm, 2003). When the electronic piece is placed into the fabric and insulated from the outside elements, the wearer can either use voice-recognition or the keyboard to operate the MP3-player in the jacket.

Webe, Glaser, Jung, Lauterbach, Stromberg and Sturm (2003) also demonstrate that it is possible to employ e-textiles in order to reclaim heat generated by the body and use that energy to generate small amounts of electricity. Heat can be reclaimed from the body through the use of thermogenerators, which are a large number of thermocouples over a section of the body, employing the Seebeck effect in order to generate voltage. The Seebeck effect is the conversion of temperature changes into electricity, which is caused by an electric field being generated when metals of differing temperatures come into contact with each other (Webe, Glaser, Jung, Lauterbach, Stromberg and Sturm, 2003). In order to ensure that the ambient temperature does not have too great of an effect upon the thermocouples, the thermogenerator is embedded into the fabric where it maintains close thermal contact to the skin. By reclaiming this heat and turning it into voltage, it is possible to generate power of 1.6 $\mu W/cm^2$, which is equivalent to the power needed to operate a wrist watch (Webe, Glaser, Jung, Lauterbach, Stromberg and Sturm, 2003).

It is also possible to use e-textiles as a transponder system to create radio frequency identification tags (RFIDs). It is possible to place RFIDs into the structure of textiles because of the size of these instruments (1 mm^2) and the low cost that is associated with constructing the RFIDs (Webe, Glaser, Jung, Lauterbach, Stromberg and Sturm, 2003). In order to integrate the RFIDs into the fabrics, conductive warp and weft threads are utilized, as the antennas used in RFIDs are not sturdy enough to withstand the environments encountered by textiles. The conductive threads are fully integrated into the fabric while minimizing the amount of contact that could potentially damage the antenna.

Electronic Textiles and Human Biological Measurements

While some e-textiles can be developed mainly for the aesthetics, researchers like Luprano, Sola i Carlos, Ridolfi, Pasche and Gros (2007) have researched and developed several biochemical and bioelectrical sensors that could be incorporated into fabrics. One area of interest is measuring the amount of sweat that is produced by the human body, which can be measured by using an ionic sensor, a pH sensor or a sweat rate sensor. An ionic sensor operates through the use of voltammetry, which limits the amount of voltage that passes through a system in order to obtain a current, which is then measured in amperes (Luprano, Sola i Carlos, Ridolfi, Pasche and Gros, 2007). In textiles, this types of sensor could be created with the use of hydrophobic and hydrophilic yarns, which would guide the sweat so it can be measured by the ionic sensor (Luprano, Sola i Carlos, Ridolfi, Pasche and Gros, 2007). A pH sensor operates through the use of a wearable pH sensor, which can determine the acidity or basicity of the sweat that is being produced (Luprano, Sola i Carlos, Ridolfi, Pasche and Gros, 2007). This type of sensor could have multiple uses, as the pH of sweat can depend on both the activity that is being performed and the state of health for the individual (. As for the sweat rate sensor, the sweat is guided by a textile membrane separating two textile electrodes and behaves in the same manner as a capacitor. When the sweat enters the sensing area, the capacitance will change, allowing for the amount of sweating to be measured (Luprano, Sola i Carlos, Ridolfi, Pasche and Gros, 2007).

Research into the use of e-textiles on workers in a factory for a more ergonomic approach has also been examined, as Ueyama, Watanabe, and Matsuoka (2003) have developed sensors that measure the workload a body is subjected to during normal operations. The sensors are placed within the uniform of the factory worker, constantly measuring and transmitting data to a central computer, allowing supervisors to determine the amount of work that is being accomplished by a worker and if the worker is having any physical issues (Ueyama, Watanabe, and Matsuoka, 2003). In order to simulate the amount of work that the body is undertaking at a given point in time, different types of sensors will be placed in various parts of the body, as each body part undergoes different types of stress. The test subjects will then perform various tasks, such as standing, walking, stretching, and the lifting of a dumbbell, with oxygen intake and energy consumption measuring during each operation (Ueyama, Watanabe, and Matsuoka, 2003). It is with this ergonomic research that e-textiles will be implemented within workplace safety, decreasing the chances of a workplace accident.

Another area where e-textiles have a possible application is the measuring the frequency of breathing by the wearer, according to the research conducted by Zięba and Frydrysiak (2006). In their research, electro-conductive yarns were placed into woven and knitted e-textiles in order to determine the ability for an e-textile to measure breathing rates. In Zięba and Frydrysiak's testing, the electro-conductive yarns consisted of polyacrylonitrile staple fibers and copper sulphides. In order to create a piece that could be worn, both a woven fabric was fabricated that consisted of a 48% cotton, 50% polyester and 2% of either electro-conductive yarns or optical fibers, while the knitted fabric was made up of cotton yarns with either electro-conductive yarns or optical fibers, knitted into a 2/2 welt stitch (Zięba and Frydrysiak, 2006).

In order to ensure that the fabric would be able to fit across the mid section of the wearer, Zięba and Frydrysiak determined that the knitted e-textile would be used in order to construct the breathing rate recorder. One difficulty that was encountered by Zięba and Frydrysiak was being able to connect the conductive fibers to a measurement device. In order to address the issue, electro-conductive glue (based on silver) was used to join the copper surfaces with yarns because of its high conductivity (Zięba and Frydrysiak, 2006).

In the area of e-textiles and human body temperature measurement, some researchers have tried to develop methods in order to measure the skin temperature of the wearer of a certain garment. In a study conducted by Deng and Liu (2008), the researchers attempted to determine how types of sensors varied in measuring skin temperature by simply gluing the thermocouples onto the skin. Deng and Liu compared the measurements obtained by both super gluing the thermocouple to skin and attaching to the body via a fabric bandage (.5 and 1mm thickness). The wearer would then simply wear the sensor for a time period of 600 seconds, with no apparent physical exercise or exertion. (Deng and Liu, 2008). The results showed that while for the sensors super glued on had a general decrease during testing, while the fabric applied thermocouples increased from a base temperature, eventually reaching a plateau around 31-32ºC. The authors also postulated that as the amount of fabric that is used in the thermocouple sensor is increased, the amount of error that is generated during testing would increase, as the fabric could potentially interfere with the temperature readings (Deng and Liu, 2008).

Research has also been conducted on making the textiles themselves act as thermocouples, as Ziegler and Frydrysiak in 2009 created thermocouple components out of textile material itself, as opposed to the implementation of traditional (metal) thermocouple wiring. In this research, Ziegler and Frydrysiak employed woven, knitted and non-woven structures to incorporate the textile-based thermocouples. The textiles that were analyzed and used for thermocouples in their study include a steel thread Bekinox, Thread of Nitril, thread of Xsilver, graphite nonwoven, a woven fabric with Nitril–Static fibers, and steel knitting. For comparison, the authors also analyzed the thermocouple capabilities of a constantan wire of 0.2 mm diameter electrically isolated with a cotton nonwoven used as electrical layer isolation, preventing electrical current being transferred outside of the thermocouple wiring into the outside environment (Ziegler and Frydrysiak, 2009). Under analysis, it was found that the thermocouples consisting of the graphite nonwoven and Xsilver thread (TTFL), the steel yarn and Nitril–Static yarn thermocouple (TTL) and the graphite nonwoven and woven fabric with Nitril-Static fiber thermocouples (TTF) were the least sensitive of the textile thermocouples, with the thermocouple made up of steel knitted fabric and constantan wire (TTH) being the most sensitive of all of the textile thermocouples tested in the study. However, when compared to traditional thermocouples the textile thermocouples are not as sensitive, with the most sensitive textile thermocouple only being somewhat comparable because it consisted of a constantan material that is commonly used in commercial thermocouples. For instance, while the Type K thermocouple used in industry today has a sensitivity of 41 µV/°C, the textile thermocouples examined in this experiment had an average sensitivity of 6.4 µV/°C (Ziegler and Frydrysiak, 2009).

CHAPTER 3 - Experimental Methodology

Introduction and Purpose

In order to test the hypotheses put forth, experimental methods were utilized in order to ensure that the research questions for this study were answered. The materials for construction were first chosen based on their ease of use, as well as the sensor's ability to measure temperature while being placed within a fabric structure. Multiple temperature sensor types were utilized in order to test whether the type of sensor utilized would have an impact on the durability of the sensor, as well as the accuracy of the temperature readings. The fabric samples were then prepared through weaving, knitting, and stitching. The temperature sensors were calibrated after insertion into the fabric samples. The various sample preparation methods were used to determine whether the methods used to make the samples had a measurable impact upon the accuracy and durability of the temperature sensors. After calibration, the fabric samples were then subjected to 20 hand washes, with temperature readings conducted after 1, 3, 5, 10, and 20 hand washes, and a statistical analysis was run on the data generated from the temperature measurements. After hand washing it was determined whether the washing of the fabric samples had a measureable impact upon the durability and the accuracy of the sensors placed within the fabric samples.

Materials Selection

Yarn

For this experiment, a 10/2 100% cotton yarn was used to construct all of the fabric samples, as this would prevent the yarn type used from varying between the fabric samples. In order to determine whether the incorporation method had a measureable effect on the accuracy and durability of the temperature sensors, fabric samples were woven and knitted, with sensors placed within the fabric structure during construction, as well as stitched onto the fabrics after the weaving and knitting process.

Weaving Loom

For this research, three woven fabric samples were constructed to contain embedded temperature sensor wiring, as it was postulated that a woven fabric structure would be rigid enough to prevent damage to thermocouple wiring due to stretching. To weave the fabric samples, a 24" wide four-harness table loom was utilized, and the yarns were woven into a basic plain weave pattern fabric structure in the weft direction. Basic plain weave was utilized for this research due to both simplicity and the limited amount of stress the weaving process would have upon the wires being placed within the woven fabrics.

The amount of yarn needed to form the warp direction was determined by the equations shown in Figures 3.1 through 3.3.

Figure 3.1: Total Length of Warp Direction of Fabric (Eads, 2010)

$$L + T + S + LW = A,$$

where L is the project length, T is the amount of take up, S is the amount of Shrinkage, LW is the amount of loom waste, and A is equal to the total length of the warp direction of the fabric.

Figure 3.2: Total Warp Ends of Fabric (Eads, 2010)

$$W + D + S = R \times EI = B,$$

where W is the finished width of the fabric, D is the draw-in, R is the width in the reed, EI is the number of ends per inch, and B is the total number of warp ends in the fabric.

Figure 3.3: Total Number of Yards of Warp Yarn Needed (Eads, 2010)

$$(A \times B) / 36 \; inches \; in \; a \; yard = \Gamma$$

where Γ equals the total amount of yards needed to generate the warp direction of the fabric (Eads, 2010).

When the equations in Figures 3.1 through 3.3 are used, it must be noted that the eventual width of the warp section of the fabric will be at least 22 inches, as shrinkage and draw-in will reduce the width of the eventual fabric sample to be obtained. The amount of yarn needed to form the filling direction is determined by the equations shown in Figures 3.4 and 3.5.

Figure 3.4: Inches of Weft for One Inch of Weaving (Eads, 2010)

$$P \times PI = \Delta,$$

where P is equal to the length of the weft pick, PI are the picks per inch, and Δ is equal to the number of inches of weft for one inch of weaving.

Figure 3.5: Total Weft Need in Yards (Eads, 2010)

$$\Delta \times IW = \frac{WN}{36\ inches\ in\ a\ yard} = E,$$

where IW is equal to the total number of inches to be woven, WN is the total weft need in inches, and E represents the total weft need in yards (Eads, 2010).

When both of the values generated from Figures 3.1 through 3.5 were obtained, it was then possible to determine the amount of yarn that would be needed to weave a sample that would measure at least 22 by 22 inches in dimensions. Once both the warp and filling yarn requirements were calculated, it was then possible to determine the total amount of yarn needed to weave the fabric by adding the totals together, with the values shown in Table 3.1.

Table 3.1: Total Amount of 10/2 Cotton Yarn Needed

Warp Yarn Needed	Filling Yarn Needed	Total Yarn Needed
1040 yards	256 yards	1296 yards

Knitting Machine

For this research, three machine-knitted fabric samples were constructed to contain embedded temperature sensor wiring, as it was postulated that knitted fabric would be able to hold sensor wires in place and prevent sensor migration. To knit the fabric samples, a flatbed knitting machine was utilized, with the yarns knitted into a basic plain jersey knit pattern fabric structure. A plain jersey knit was used for this research due to the simplicity and ease of construction with the use of a knitting machine.

In order to knit samples that would be the same size as the woven samples, 154 latch hook needles were used on the knitting machine, with 7 stitches per inch and a stitch size of 6 (SS6) to knit a fabric that was 22 inches wide. These settings generated a knit pattern where there were 10 rows of knitting per inch of fabric, with a total of 220 rows of knitting required to knit a sample 22 inches long.

Thermocouple Preparation

To record temperature measurements during testing, thermocouples were embedded within the woven and knitted samples. With the eventual goal of designing a garment that can be used in environments that would be encountered by humans in nature, the Type T thermocouple was used in order to record the temperatures measured within the woven and knitted samples. The Type T thermocouple was suitable for this use, as its temperature range is -200°C to 371°C, which covers both the extreme cold and hot temperatures. During the preparation of the samples, four thermocouples were embedded within each of three woven and knitted samples, resulting in a total of 24 thermocouples that were needed for experimentation. Of the thermocouples that were inserted into the samples, two of the thermocouples had outer insulation to keep the thermocouple wires together, while the other two thermocouples were stripped of their outer insulation, leaving the welded tip in place. In order to make sure that each thermocouple would fit into the woven and knitted fabric without altering any of the fabric properties, the thermocouple also had a gauge that were similar in size or smaller than the yarns that were being woven and knitted. For this experiment, the thermocouple wiring was 30 gauge, meaning that the thermocouple wiring has a diameter of 0.255 millimeters, or 0.01 inches.

Preparation of Resistance Temperature Directors

To record temperature measurements during testing, resistance temperature directors (RTDs) were embedded within the woven and knitted samples. With the eventual goal of designing a garment that can be used in environments that would be encountered by humans in nature, a 1.1 meter copper RTD wire was used in order to record the temperatures measured within the woven and knitted samples. The copper wire RTD was suitable for this use, as it can measure temperatures up to 600°C, which covers extreme temperatures. During the preparation of the samples, two copper RTD wires were embedded within each of three woven and knitted samples, resulting in a total of 12 copper RTD wires for experimentation. Like the thermocouples used in this research, the RTD wiring was 30 gauge, meaning that the wiring had a diameter of 0.255 millimeters, or 0.01 inches, in order to make sure that each RTD would fit into the woven and knitted fabric without altering any of the fabric properties.

Weaving and Knitting of the Sample Fabrics

Warping the Loom

When weaving a fabric, the loom must first be warped, as this will generate the warp direction of the samples. To warp the loom, the number of warp ends for each type of yarn was measured to 60 inches, with each end being placed threaded through the reed and heddles. In order to form floating selvages, the first and last warp ends of the yarns were left out of the heddles, helping create edges that will not fray when placed under stress. The ends were then tied to the back apron bar of the loom, allowing the yarns to be wound onto the warp beam, making sure that the yarns did not become entangled when they were wound onto the warp beam. After adjusting the tension on the beam to an appropriate level, the warp direction of the fabric sample was created.

Insertion of Weft Yarns and Temperature Sensors

To form the weft direction of the fabric, a boat shuttle bobbin was first wound with the filling yarn. Once the shuttle bobbin was wound, the weaving process began when three picks of filling yarn were woven without beating, after which all three picks were beaten at the same time in order to even the tension and spacing across the width of the weaving. After the tension and spacing was even, 8 inches of the fabric was woven in a plain weave structure, with the first insulated thermocouple being woven in at the 8 inch point through insertion in the weft direction. Two additional inches of fabric was then woven, with the first un-insulated thermocouple wiring being woven into the fabric, with the thermocouple wires separated by 0.5 inches of woven fabric and the weld point above the surface of the fabric. Two additional inches of fabric was then woven. The copper RTD wire was woven into the fabric, with one end of the copper wire separated from the other end by 0.5 inches of woven fabric, with the other end of the copper wire inserted through the weft direction. After the copper RTD wire was woven into the fabric, 8 inches of fabric was then woven, and the 22 inch by 22 inch fabric sample was completely woven. The process was repeated two more times in order to weave three fabric samples. After weaving was completed the weave was cut off the loom, leaving at least 3 inches of unwoven warp at each end of the weaving. A diluted glue adhesive was applied to the ends of the samples to prevent unraveling during testing.

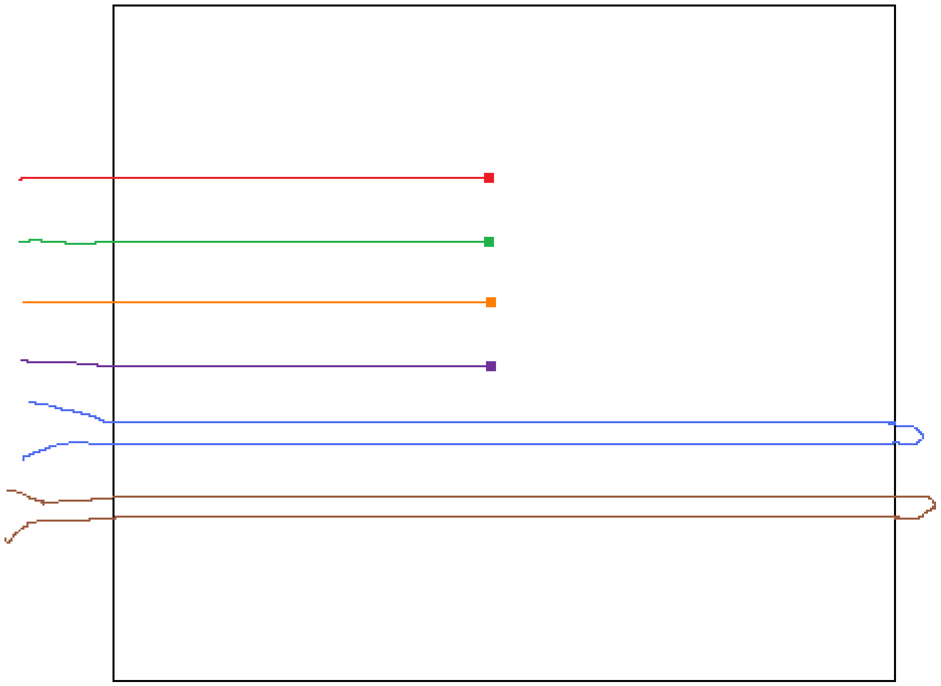
Knitting of Fabric and Interlacing of Temperature Sensors

Once the cotton yarn was drawn through the carriage and the 154 latch hook needles in the knitting machine, the knitting process began by pushing the carriage across the latch hook needles, creating a knit pattern. Weights were placed on the fabric to prevent shrinkage after 20 knitting rows were completed, and 80 additional rows of knitting were completed. With 80 rows of knitting completed, an insulated thermocouple was then interlaced into knitted fabric into the knitted fabric structure by guiding the thermocouple through the latch hook needles, making sure that the thermocouple would be caught between every third stitch. 20 additional rows of knitting were then completed. An un-insulated thermocouple wiring was interlaced into knitted fabric into the fabric following the same process as established with the insulated thermocouples, with the thermocouple wires separated by 5 rows of knit. 20 additional rows of knit were then completed. The copper RTD wire was interlaced into knitted fabric into the fabric, with one end of the copper wire separated from the other end by 5 rows of knit. After the copper RTD wire was woven into the fabric, 80 more rows of knit fabric were then made, completing the 22 inch by 22 inch fabric sample. The process was repeated two more times in order to knit three fabric samples. After knitting was completed, an adhesive coating was applied to the borders of the fabrics in order to prevent unraveling of the samples.

Stitching of Temperature Sensors onto Fabric Samples

After the woven and knitted fabrics were completed, temperature sensors were then attached to each of the fabric samples with 50wt polyester thread and a 304 zig-zag lockstitch for each sensor with the use of a sewing machine. To stitch the insulated thermocouples onto the samples, one inch was measured from where the insulated thermocouple was woven/interlaced into the fabric, and the thermocouple was then stitched onto the fabric sample. The un-insulated thermocouple was stitched onto the fabric sample one inch from the un-insulated thermocouple that was woven/interlaced into the fabric, with the thermocouple wires separated by 0.5 inches. The copper RTD wire was then stitched onto the fabric sample one inch from the copper RTD that was woven/interlaced into knitted fabric into the fabric, with the thermocouple wires separated by 0.5 inches. An example of the fabric samples produced is shown in Figure 3.6.

Figure 3.6: 22" x 22" Fabric Samples with Thermocouples and RTDs



In Figure 3.6, the red line indicates an insulated thermocouple wire woven/knit woven into the fabric, the green line indicates an insulated thermocouple that has been stitched onto the fabric, the orange line indicates an un-insulated thermocouple wire woven/knit woven into the fabric, the purple line indicates a non-insulated thermocouple that has been stitched onto the fabric, the blue lines that run parallel to each other across the width of the fabric are the copper RTD wires that have been woven/knit woven into the fabric, while the brown lines that run parallel to each other across the width of the fabric are the copper RTD wires that have been stitched onto the fabric.

Documentation of Temperature Sensor Insertion

After all of the temperature sensors were attached to the fabric samples, pictures were taken of the sensors inside the garment with the use of a rigid borescope. The samples would be placed under the sights of the borescope, which was connected to a computer in order to take pictures and save the images generated. Pictures were taken of each of the thermocouples that were able to remain in the fabric samples after construction, with pictures taken of both the temperature sensing junctions of the thermocouples and the copper RTD wiring as it was placed within the fabric structure.

Temperature Recording and Calibration of the Temperature Sensors

Recording Temperature with Thermocouples

To make a temperature measurement from a thermocouple, the thermocouple was connected to a data acquisition/data logger switch unit. The thermocouples were connected to the data acquisition device with the use of a 20 channel multiplexer, with each channel consisting of a bus that contains high and low input signal terminals. The thermocouple was connected through one channel, with the copper wire connected to the high input terminal, while the constantan wire connected to the low signal terminal. The multiplexer was then inserted into the data acquisition unit, which was able to determine a temperature reading based off of the voltage in the millivolts (mV) that was generated at the temperature reading junction.

Recording Temperature with RTDs

To generate a temperature measurement from the RTDs that were inserted into the fabric samples, the RTDs were connected to a data acquisition/data logger switch unit in a similar fashion as the thermocouples. However, a four-wire RTD connection was utilized in order to generate more accurate data from the temperature sensors in the fabric. The four-wire RTD connection was made through the use of an electrical connector and four 23 gauge insulated braided copper wires. The two un-insulated copper RTD wires from the fabric connected to one side of the electrical connector, while the four insulated copper braided wires were connected to the other side of the connector, with two insulated wires occupying each slot. The four insulated wires were then be connected to the multiplexer, with one wire occupying the high input signal of Channel 1, another wire connected to the high input signal of Channel 2, another wire connected to the low input signal of Channel 2, and the last wire was connected to the low input signal of Channel 3. Two 30 gauge un-insulated copper wires were used to connect the input signal of Channel 1 to the high input signal of Channel 2, and the low input signal of Channel 2 to the high input signal of Channel 3, completing the connection and generating 3 different resistances. The multiplexer was then inserted into the data acquisition unit, which was able to determine the resistances of each of the three channels being occupied by the four-wire RTD. In order to determine the overall resistance of the RTD, the resistance generated in Channels 1 and 3 were subtracted from Channel 2, with the resulting value being the resistance generated by 1.1 meters of the copper wire at a given temperature.

Calibration of Temperature Sensors within Fabric Samples

Sensors placed within fabric samples must be calibrated, as the temperatures generated from the sensors must be compared to a known temperature in order to correct for changes that occurred during the sample construction process. To calibrate the sensors, water set at known temperatures was used to determine the accuracy of the sensors in terms of temperature measurement.1.5 liters of water was placed into two two-gallon plastic bags, with the fabric sample placed between both of the plastic bags in order to ensure that the sensors were in contact with the same temperature throughout the fabric sample with the temperature sensors attached to the data acquisition unit. The sensors were calibrated at high temperature (37 ± 3°C), room temperature (21 ± 3°C), and cold temperature (7 ± 3°C), with the temperature sensors attached to the data acquisition unit. The readings for the thermocouples generated during calibration were analyzed in order to adjust the temperature recordings conducted during later testing, while the resistances recorded for the RTDs during calibration were analyzed to determine a linear equation that best fits the generated data. The resulting linear equation was then used later in the study to determine the temperature measurements made by the sensors after washing.

Washing of the Fabric Samples

After the temperature sensors were calibrated, the fabric samples were then hand washed and drip dried according to AATCC Test Method 124-1996 "Appearance of Fabrics after Repeated Home Laundering." To hand wash the fabrics, 20.0 ± 0.1g of 1993 AATCC Standard Reference Detergent was first dissolved into 7.57 ± 0.06L of water at 41 ± 3°C in a 9.5 L pail, with three fabric samples added afterwards. The fabrics were then washed for 2.0 ± 0.1 min with no twisting or wringing, and then rinsed once using 7.57 ± 0.06L of water at 41 ± 3°C (AATCC Test Method 124-1996, 1996). After washing, the fabric samples were then hung to dry by two corners of the sample, allowing the samples to hang in still air at room temperature until dry. The hand washing and drying process was repeated 20 times, with the temperature sensors being tested for durability and accuracy after 1, 3, 5, 10, and 20 hand washes.

Testing of the Fabric Samples

To test the durability and accuracy of the temperature sensors after washing, the thermal sensors were tested with water set at known temperatures to determine the accuracy of the sensors.1.5 liters of water was placed into two two-gallon plastic bags, with the fabric sample placed between both of the plastic bags in order to ensure that the sensors were in contact with the same temperature throughout the fabric sample with the temperature sensors attached to the data acquisition unit. The temperatures were measured at high temperature (37 ± 3°C) and room temperature (21 ± 3°C). The procedure was then repeated for every sample made, and was conducted after 1, 3, 5, 10, and 20 hand washes.

Data Analysis

When testing was completed, the various types of data generated were then analyzed to determine how the temperature sensors were able to withstand stress from construction and washing, as well as their reliability in terms of measuring the temperature accurately. In order to measure the accuracy of the temperature sensors before and after hand washings, the temperature recorded by the sensors during both room temperature and hot temperature measurements were compared to the actual temperature of the water that was placed in the plastic bags that surrounded the fabric samples, which was measured through the use of a calibrated thermocouple. It was through comparing the accuracy of the temperature sensors that it was possible to determine if certain sensor types were more or less accurate in measurement, as well as to determine if the washing of the samples had an impact upon the accuracy of the temperature sensors.

To determine whether there was a measureable difference in durability and the ability to measure temperature accurately between the insulated thermocouples, un-insulated thermocouples, and copper RTD wires after insertion, the temperature recordings conducted before and after hand washing were analyzed using two-way analyses of variation, determining the mean and standard deviation for all of the sensor types used in constructing the fabric samples.

CHAPTER 4 - Results

With the implementation of numerous temperature sensors in the fabric samples, it was necessary to create a code system for each of the sensors used for the study. To generate a code for each of the sensors, the code generated was based off of the fabric sample it was placed in, the type of sensor that was being identified, and how the sensor was incorporated into the fabric sample. For instance, the un-insulated thermocouple that was stitched onto the first woven sample was coded as W1US (Woven Sample 1, Un-insulated thermocouple, Stitched on). In order to list all of the sensors used, grids have been generated to show the codes for each sensor (Tables 4.1 and 4.2).

Table 4.1: Coding For Temperature Sensors in Woven Samples

Fabric Sample	Sensor Type	Incorporation Method	Sensor Code
Woven Sample 1	Insulated Thermocouple	Weaving	W1IW
Woven Sample 1	Insulated Thermocouple	Stitching	W1IS
Woven Sample 1	Un-insulated Thermocouple	Weaving	W1UW
Woven Sample 1	Un-insulated Thermocouple	Stitching	W1US
Woven Sample 1	RTD	Weaving	W1RW
Woven Sample 1	RTD	Stitching	W1RS
Woven Sample 2	Insulated Thermocouple	Weaving	W2IW
Woven Sample 2	Insulated Thermocouple	Stitching	W2IS
Woven Sample 2	Un-insulated Thermocouple	Weaving	W2UW
Woven Sample 2	Un-insulated Thermocouple	Stitching	W2US
Woven Sample 2	RTD	Weaving	W2RW
Woven Sample 2	RTD	Stitching	W2RS
Woven Sample 3	Insulated Thermocouple	Weaving	W3IW
Woven Sample 3	Insulated Thermocouple	Stitching	W3IS
Woven Sample 3	Un-insulated Thermocouple	Weaving	W3UW
Woven Sample 3	Un-insulated Thermocouple	Stitching	W3US
Woven Sample 3	RTD	Weaving	W3RW
Woven Sample 3	RTD	Stitching	W3RS

Table 4.2: Coding For Temperature Sensors in Knitted Samples

Fabric Sample	Sensor Type	Incorporation Method	Sensor Code
Knitted Sample 1	Insulated Thermocouple	Knit-Weaving	K1IK
Knitted Sample 1	Insulated Thermocouple	Stitching	K1IS
Knitted Sample 1	Un-insulated Thermocouple	Knit-Weaving	K1UK
Knitted Sample 1	Un-insulated Thermocouple	Stitching	K1US
Knitted Sample 1	RTD	Knit-Weaving	K1RK
Knitted Sample 1	RTD	Stitching	K1RS
Knitted Sample 2	Insulated Thermocouple	Knit-Weaving	K2IK
Knitted Sample 2	Insulated Thermocouple	Stitching	K2IS
Knitted Sample 2	Un-insulated Thermocouple	Knit-Weaving	K2UK
Knitted Sample 2	Un-insulated Thermocouple	Stitching	K2US
Knitted Sample 2	RTD	Knit-Weaving	K2RK
Knitted Sample 2	RTD	Stitching	K2RS
Knitted Sample 3	Insulated Thermocouple	Knit-Weaving	K3IK
Knitted Sample 3	Insulated Thermocouple	Stitching	K3IS
Knitted Sample 3	Un-insulated Thermocouple	Knit-Weaving	K3UK
Knitted Sample 3	Un-insulated Thermocouple	Stitching	K3US
Knitted Sample 3	RTD	Knit-Weaving	K3RK
Knitted Sample 3	RTD	Stitching	K3RS

Construction of Samples

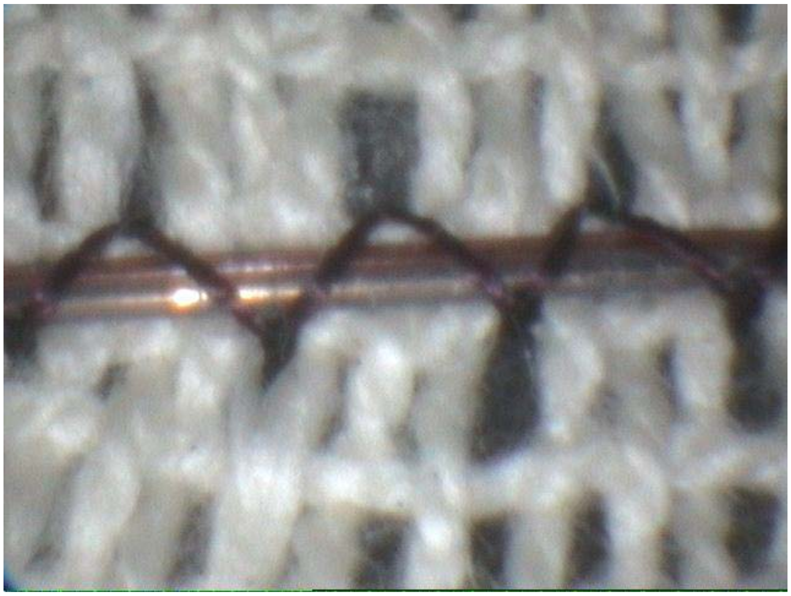
Woven Fabrics

The insulated thermocouples that had been woven into the fabric were unaltered in terms of kinking and bending (Figure 4.1), but had a high range of movement within the fabric due to the openness of the weave and the lower thread count. This wide range of movement eventually led to the failure of all of the woven in insulated thermocouples, as the temperature sensors slipped out of the woven fabric structure before the 20 hand wash cycles were completed.

Figure 4.1: Insulated Thermocouple Woven inside Fabric

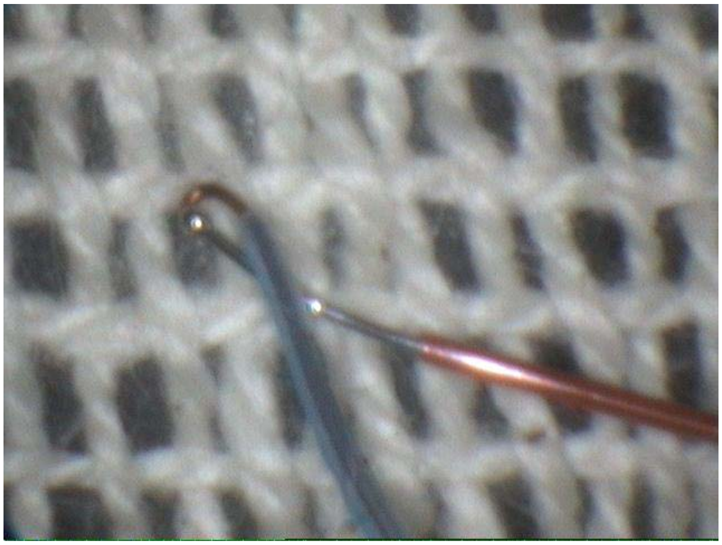
While the insulated thermocouples that were woven into the fabric structure had a high range of movement, the insulated thermocouples that had been stitched onto the woven fabric had a moderate range of movement, while at the same time not damaging any of the thermocouples (Figure 4.2). This lack of movement made the stitched in insulated thermocouples more durable, as only one of the thermocouples (W2IS, after 5 hand washes) was able to slip out of the stitching during the washing cycles.

Figure 4.2: Insulated Thermocouple Stitched on Woven Fabric



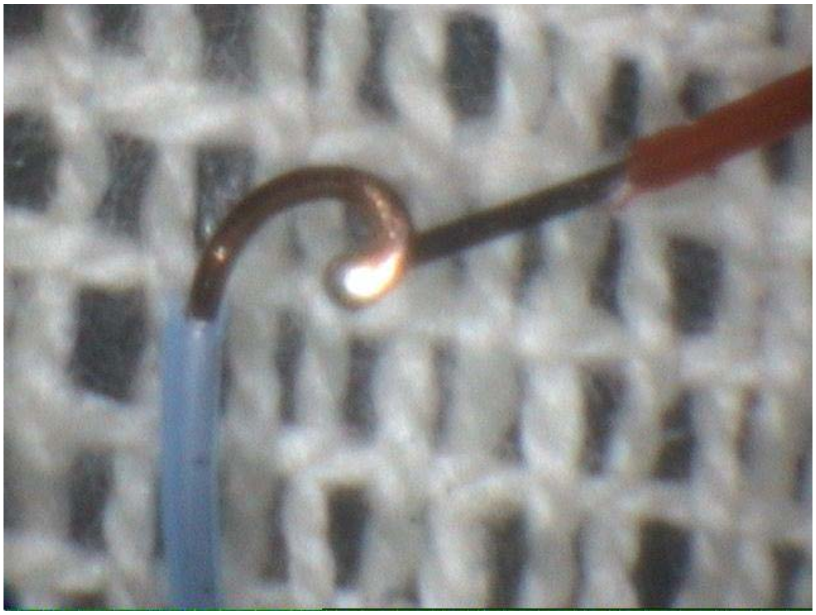
The un-insulated thermocouples had a high range of movement within the fabric, which was similar to the insulated thermocouples that had been woven into the fabric. However, the removal of the insulation separating the two wires of the thermocouple allowed for kinking and bending of the thermocouples, with twisting at the point of measurement (Figure 4.3). This twisting weakened the soldering at the measuring point, and the subsequent hand washing was able to break all but one of the un-insulated thermocouples.

Figure 4.3: Un-insulated Thermocouple Woven inside Fabric



The stitched in un-insulated thermocouples had a moderate range of movement within the fabric. However, like the un-insulated thermocouples that had been woven in, the two wires of the thermocouple were kinked and bent, with twisting at the point of measurement (Figure 4.4). However, the lack of the ability for the thermocouple to move prevented any additional stress to be placed onto the soldered junction, as all three of the sensors were able to withstand 20 hand wash cycles.

Figure 4.4: Un-insulated Thermocouple Stitched on Woven Fabric

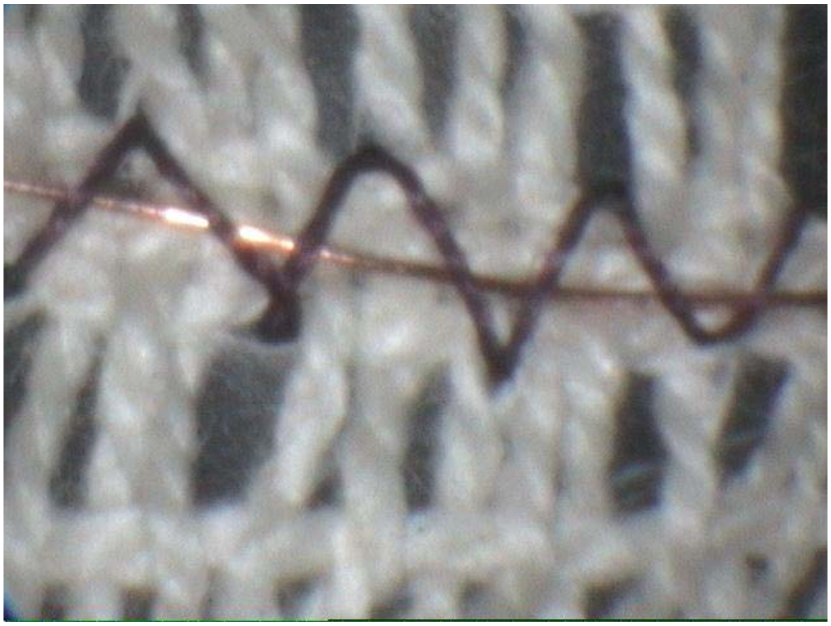


The copper RTD wire that was woven into the fabric structure had a small range of movement, and there was very little bending of the copper wire (Figure 4.5). This lack of bending by the RTD allowed the resistance to flow throughout the copper wire, with the weaving process having no effect on the operability of the RTD.

Figure 4.5: Woven in RTD in Woven Fabric

The copper RTD wire that was stitched onto the woven fabric structure was similar to the RTD wire that was woven into the fabric structure, as it had a small range of movement, and there was very little bending of the copper wire, with the weaving process having very little impact on the operability of the temperature sensor (Figure 4.6).

Figure 4.6: RTD Stitched on Woven Fabric



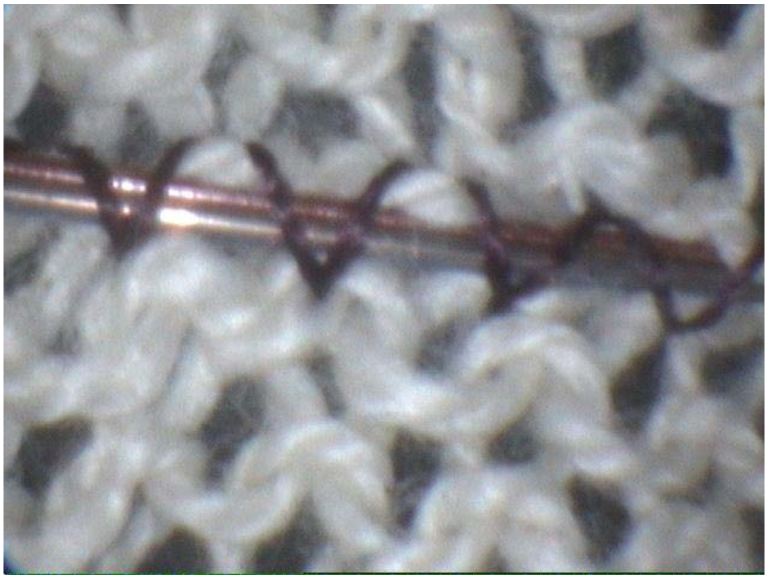
Knitted Fabrics

The insulated thermocouple that was knitted into the fabric structure had a moderate range of movement, as the bending of the thermocouple wires into the knit structure lessened the ability of the thermocouple to move within the fabric structure (Figure 4.7). However, K1IK was unable to contain the insulated thermocouple, and the thermocouple fell out of the sample after the sample was removed from the knitting machine.

Figure 4.7: Insulated Thermocouple Interlaced into Knitted Fabric

The insulated thermocouple that was stitched onto the knitted fabric had a low range of movement. However, unlike the knitted insulated thermocouples, all of the thermocouples were stitched onto the knitted fabrics without any broken thermocouples, and the stitching allowed the thermocouples to remain on the knit fabrics after 20 hand wash cycles (Figure 4.8).

Figure 4.8: Insulated Thermocouple Stitched on Knitted Fabric

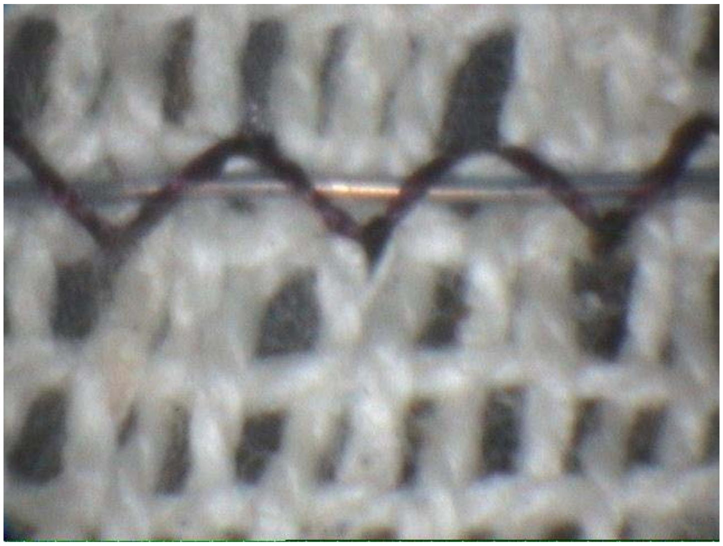


The un-insulated thermocouple that was knitted into the fabric structure had a small range of movement, as the bending of the thermocouple wires lessened the ability of the thermocouple to move within the fabric structure (Figure 4.9). However, like the knitted in insulated thermocouples, one of the un-insulated thermocouples broke during the knitting process, as the bending caused the soldering of the junction, where temperature measurement takes place, to break. The kinking caused by the knit structure prevented any other breakages during washing, as decreased movement prevented additional stress from being placed onto the junction points.

Figure 4.9: Un-insulated Thermocouple Interlaced into Knitted Fabric

The un-insulated thermocouples that were stitched onto the knitted fabrics had both a small range of movement and were not bent along their length (Figure 4.10). However, like other un-insulated thermocouples that were utilized, these thermocouples were bent at the junction where temperature measurements take place. The bending resulted in K3US breaking during the stitching process, as the soldering snapped when the thermocouple wire that was not stitched in moved while the other end of the thermocouple wire was being stitched into place on the knitted fabric.

Figure 4.10: Un-insulated Thermocouple Stitched on Knitted Fabric



The copper RTD wires that were knitted into the fabric structure were unable to withstand the pressures of construction. All of the copper RTD wires bent and broke during the knitting process (Figure 4.11).

Figure 4.11: RTD Sensor Interlaced into Knitted Fabric

Unlike the copper RTD wire that was interlaced into knitted fabric structure, the RTD wire that was stitched onto the knitted fabric surface did not break, and had characteristics that were similar to the copper wire that was stitched onto the surface of the woven fabric samples (Figure 4.12). The stitching was able to hold the RTD in place, as there were no broken RTD wires after 20 hand wash cycles.

Figure 4.12: RTD Stitched on Knitted Fabric

Calibration of Sensors within Fabrics

Woven Fabrics

When calibration was performed on the thermocouples in the woven fabrics, the thermocouples in the first fabric sample were consistently near the temperature being applied to the fabric sample at all temperature measurements within 1°C, as shown in Table 4.3. However, the thermocouples in the second and third woven samples were consistently off from the target temperature at the hot temperature measurements, as each of the measurements was higher than the actual temperature by an average of 2°C. These inaccuracies lead to an adjustment of temperature readings that were to be obtained in later measurements, with 2°C subtracted from the hot temperature measurements from the second and third woven samples after hand washings.

In the knitted fabrics, all of the thermocouples in the first and second knitted fabric were consistent in terms of accurately measuring the temperature, as they were all within 1°C of measuring the temperature correctly. However, the thermocouples that were placed within the third knitted fabric were consistently off from the actual temperature, as they were on average 1.5°C higher than the actual temperature recorded during the hot temperature measurements. To correct for the temperature difference, 1.5°C was subtracted from the hot temperature measurements that were made after hand washing.

Table 4.3: Recorded Temperatures of Thermocouples during Calibration (in °C)

Sensor	Cold Temperature	Room Temperature	Hot Temperature
W1IW	9.7	23	36.9
W1IS	10.8	23.2	36.2
W1UW	11.2	23.1	36.9
W1US	9.8	22.6	37.3
W2IW	11.7	21.4	38.8
W2IS	9.9	21.5	40.7
W2UW	9.1	21.3	40.8
W2US	8	21.4	41.1
W3IW	5	21.2	41.3
W3IS	5.3	21.5	41.4
W3UW	4.6	21.2	41.4
W3US	4.4	21.4	41.6
K1IK	broken		
K1IS	3.3	21	38.8
K1UK	2.2	21.2	38.6
K1US	3	21.1	38.6
K2IK	3.8	21.1	36.8
K2IS	3.4	21	37.2
K2UK	broken		
K2US	3.2	21	37.6
K3IK	3.1	21.3	39.8
K3IS	3.2	21.6	39.9
K3UK	3	21.5	40.1
K3US	broken		
Control	9.5	23	37.5

Knitted Fabrics

During the calibration process for the RTDs placed within the woven fabrics, almost all of the resistances obtained were consistent for both the woven-in and the stitched-in RTDs. However, the RTD that was stitched on the first sample generated resistances that were lower in comparison to the other RTDs for the woven fabric samples. The resistances recorded during the calibration were used to generate linear equations that would determine a temperature when a resistance is known.

When the RTDs in the knitted fabrics were calibrated, the knitted copper wire was broken, so no resistance was recorded during the calibration process. As for the stitched-in RTDs, the resistances measurements varied, as none of the RTDs measured within .01 ohms of each other, causing each of the linear equations generated from readings to be drastically different, as shown in Table 4.4.

The linear equations generated from the resistance recordings during calibration were used to determine the temperature recordings after the washing of the fabric samples by entering in the recorded resistance for x into the linear equation for the specific RTD (Table 4.5). It was then possible to determine the temperature based on the resistance that was recorded by solving the equation for y.

Table 4.4: Recorded Resistances of RTDs during Calibration (in Ohms)

Sensor	Cold Temperature	Room Temperature	Hot Temperature
W1RW	0.287	0.308	0.334
W1RS	0.274	0.2994	0.318
W2RW	0.29	0.311	0.334
W2RS	0.2979	0.315	0.3346
W3RW	0.302	0.3264	0.344
W3RS	0.282	0.3205	0.331
K1RK	broken		
K1RS	0.2302	0.2508	0.268
K2RK	broken		
K2RS	0.2469	0.2637	0.283
K3RK	broken		
K3RS	0.2597	0.2761	0.301

Table 4.5: Linear Equations For RTDs in Fabric Samples

Temperature Sensor	Linear Equation
W1RW	y = 538.4x-143.0
W1RS	y = 752.6x-202.5
W2RW	y = 826.0x-235.4
W2RS	y = 969.3x-283.8
W3RW	y = 1136.3x-349.6
W3RS	y = 1904.7x-589.1
K1RS	y = 1017.4x-233.9
K2RS	y = 844.5x-201.7
K3RS	y = 738.9x-182.5

Sensor Testing

Woven Fabrics

During the testing of the insulated thermocouples that were woven into the fabric structure, the sensors were consistent with the temperature that was supplied, as there were only two instances where the actual temperature varied from the recorded temperature by more than 1°C. The first woven in insulated thermocouple that broke was W3IW. The woven structure was not tight enough to contain a thermocouple of that size and it slipped out of the fabric after the third washing. The other two insulated thermocouple samples ended up slipping out in the same fashion as well, as W1IW came out after the fifth washing, and W2IW came out after ten washes (Tables 4.6 through 4.9). The looseness of the woven structure and the size of the thermocouples would continue to be a major issue in the insulated thermocouples that were placed within both the woven and knit fabric samples.

Table 4.6: Difference of Recorded Temperature from Actual Temperature with Woven in Insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1IW	0.1	0.2	0.1	broken			0.1333333
W2IW	0.3	0.3	0.4	0.1	broken		0.275
W3IW	0.4	0.2	broken				0.3

Table 4.7: Difference of Recorded Temperature from Actual Temperature with Woven in Insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1IW	0.2	1.3	0.6	broken			0.7
W2IW	0.7	0.1	0	0.5	broken		0.325
W3IW	2.4	0.1	broken				1.25

Table 4.8: Recorded Temperatures of Woven in Insulated Thermocouples at Room Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1IW	23.0	22.8	22.9	broken		
W2IW	21.4	23.2	22.2	23.2	broken	
W3IW	21.2	24.0	broken			
Mean	21.9	23.3	22.6	23.2		
Standard Deviation	1.0	0.6	0.5			
Actual Temperature	22.9					

Table 4.9: Recorded Temperatures of Woven in Insulated Thermocouples at Hot Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1IW	36.9	39.1	38.1	broken		
W2IW	38.8	38.2	37.9	36.4	broken	
W3IW	41.3	37.1	broken			
Mean	39.0	38.1	38.0	36.4		
Standard Deviation	2.2	1.0	0.1			
Actual Temperature	37.0					

When the thermocouples that have been stitched onto the woven fabrics were tested, the sensors were consistently close to the actual temperature, as there was only one instance after calibration where the thermocouple measured a temperature that was off from the actual temperature by more than 1°C. Only one of the thermocouples broke during testing, as the insulated thermocouple that was stitched on the second woven fabric sample slipped out of the woven structure after the fifth washing, while the other thermocouples were able to withstand twenty washes. The issue of the large diameter insulated thermocouples that were stitched on was not as pronounced as it was in terms of the insulated thermocouples that were woven into the fabric structure, mainly due to the stitching holding the thermocouple in place much tighter (Tables 4.10 through 4.13).

Table 4.10: Difference of Recorded Temperature from Actual Temperature with Stitched on Insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1IS	0.3	0	0.1	0.3	0.2	0.1	0.1666667
W2IS	0.2	0.1	0.2	broken			0.1666667
W3IS	0.1	0.3	0.2	0.5	0.4	0.5	0.3333333

Table 4.11: Difference of Recorded Temperature from Actual Temperature with Stitched on Insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1IS	0.9	1.3	0.5	0.1	0.1	0.8	0.6166667
W2IS	2.6	0.5	0.1	broken			1.0666667
W3IS	2.5	0.5	0.5	0.3	0.1	0.1	0.6666667

Table 4.12: Recorded Temperatures of Stitched on Insulated Thermocouples at Room Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1IS	23.2	23.0	23.1	22.8	23.3	22.9
W2IS	21.5	23.4	22.4	broken		
W3IS	21.5	24.1	23.7	22.4	22.3	23.4
Mean	22.1	23.5	23.1	22.6	22.8	23.2
Standard Deviation	1.0	0.6	0.7	0.3	0.7	0.4
Actual Temperature	22.9					

Table 4.13: Recorded Temperatures of Stitched on Insulated Thermocouples at Hot Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1IS	36.2	39.1	38.0	36.8	37.2	38.3
W2IS	40.7	38.6	38.0	broken		
W3IS	41.4	36.7	37.7	36.6	36.5	37.0
Mean	39.4	38.1	37.9	36.7	36.9	37.7
Standard Deviation	2.8	1.3	0.2	0.1	0.5	0.9
Actual Temperature	37.0					

When the un-insulated thermocouples that were woven into the fabrics were examined during testing, they were consistently close to the actual temperature that was supplied, as they were on average accurate to within one degree Celsius of all of the measurements that were taken. During testing, both the un-insulated thermocouples in the first and second woven sample broke, with the first thermocouple lasting less than ten washes, while the second thermocouple was unable to withstand five washes (Tables 4.14 through 4.17). The breakage of both of the thermocouples occurred when the soldering at the measuring junction of the thermocouple broke, as this prevented the wires from touching each other and generating a recordable voltage. The breakage of the un-insulated thermocouples was due to the spacing between the thermocouple wires and for the movement of the thermocouple wires, as each of the wires would pull away from each other during washing, placing stress on the soldered joint.

Table 4.14: Difference of Recorded Temperature from Actual Temperature with Woven in Un-insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1UW	0.2	0.1	0	0	broken		0.075
W2UW	0.4	0.5	0.1	broken			0.3333333
W3UW	0.4	0.1	0.1	0.3	0.4	0.1	0.2333333

Table 4.15: Difference of Recorded Temperature from Actual Temperature with Woven in Un-insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1UW	0.2	1.4	0.3	0.2	broken		0.525
W2UW	2.7	0.2	0.1	broken			1
W3UW	2.5	0.1	0	0.8	0.3	0.6	0.7166667

Table 4.16: Recorded Temperatures of Woven in Un-insulated Thermocouples at Room Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1UW	23.1	23.1	23.0	23.1	broken	
W2UW	21.3	24.0	22.5	broken		
W3UW	21.2	23.9	23.6	22.6	22.3	22.8
Mean	21.9	23.7	23.0	22.9	22.3	22.8
Standard Deviation	1.1	0.5	0.6	0.4		
Actual Temperature	22.9					

Table 4.17: Recorded Temperatures of Woven in Un-insulated Thermocouples at Hot Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1UW	36.9	39.2	37.2	36.7	broken	
W2UW	40.8	37.9	37.8	broken		
W3UW	41.4	37.3	37.2	36.1	36.3	37.7
Mean	39.7	38.1	37.4	36.4	36.3	37.7
Standard Deviation	2.4	1.0	0.3	0.4		
Actual Temperature	37.0					

When the stitched in un-insulated thermocouples were examined during testing, they were comparable in accuracy to the other thermocouples within the woven structures, as they deviated less than one degree Celsius after calibration adjustments were made (Tables 4.18 through 4.21). Unlike the other thermocouples, all of the stitched in un-insulated thermocouples were able to withstand twenty washes, as all of the thermocouples were able to record a temperature that was consistent with the temperature that was provided. This was due to the fact that the stitching prevented the thermocouples from moving during washing, which prevented stress from being placed upon the exposed soldered junction of the thermocouple.

Table 4.18: Difference of Recorded Temperature from Actual Temperature with Stitched on Un-insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1US	0.3	0.1	0	0.1	0.1	0.1	0.1166667
W2US	0.3	0.2	0.4	0	0.2	0.5	0.2666667
W3US	0.2	0.5	0.1	0.4	0.4	0.3	0.3166667

Table 4.19: Difference of Recorded Temperature from Actual Temperature with Stitched on Un-insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1US	0.2	0.5	0.1	0.9	0.2	0.1	0.3333333
W2US	3	0.5	0	0.8	0.3	0.2	0.8
W3US	2.7	0.3	0.1	0.1	0.5	0.5	0.7

Table 4.20: Recorded Temperatures of Stitched on Un-insulated Thermocouples at Room Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1US	22.6	23.1	23.0	23.2	23.2	23.1
W2US	21.4	23.7	22.2	23.1	23.0	22.2
W3US	21.4	24.3	23.6	22.5	22.3	23.2
Mean	21.8	23.7	22.9	22.9	22.8	22.8
Standard Deviation	0.7	0.6	0.7	0.4	0.5	0.6
Actual Temperature	22.9					

Table 4.21: Recorded Temperatures of Stitched on Un-insulated Thermocouples at Hot Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1US	37.3	37.3	37.4	36.0	37.3	37.4
W2US	41.1	38.6	37.9	36.1	37.2	36.9
W3US	41.6	37.5	37.3	36.8	36.1	37.6
Mean	40.0	37.8	37.5	36.3	36.9	37.3
Standard Deviation	2.4	0.7	0.3	0.4	0.7	0.4
Actual Temperature	37.0					

During testing, the RTDs that were woven into the fabric structure provided erratic measurements, as all of the woven in RTD generated temperatures that on average varied from the provided temperature by at least 26°C. This erratic measurement is evident in the standard deviation values generated from the measurements, as some were measured in tens of °C (Tables 4.22 through 4.25). The RTDs were able to withstand the twenty washes, as none of the RTDs broke during testing. One possible issue that may have lead to the erratic measurements from the woven in RTDs was that the electrical connectors were disconnected from the RTDs in order to hand wash the fabric samples.

Table 4.22: Difference of Recorded Temperature from Actual Temperature with Woven in RTDs at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1RW	0.1	24.56923077	19.023077	21.5076923	104.7	31.5692308	33.578205
W2RW	0.2	42.69130435	23.765217	26.9	32.9956522	47.126087	28.946377
W3RW	0.3	28.86363636	15.527273	20.6727273	19.7363636	71.8090909	26.151515

Table 4.23: Difference of Recorded Temperature from Actual Temperature with Woven in RTDs at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1RW	0.3	14.56153846	12.169231	18.2076923	93.9307692	38.6076923	29.629487
W2RW	2.4	36.26956522	31.513043	26.7304348	26.7304348	47.1826087	28.471014
W3RW	2.4	22.28181818	26.827273	22.5818182	28.5636364	89.4272727	32.013636

Table 4.24: Recorded Temperatures of Woven in RTDs at Room Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1RW	22.8	47.6	42.0	44.6	127.8	54.6
W2RW	21.5	66.2	46.4	50.0	56.2	69.8
W3RW	21.3	52.7	39.0	43.6	42.4	94.7
Mean	21.9	55.5	42.5	46.1	75.5	73.0
Standard Deviation	0.8	9.6	3.7	3.5	45.8	20.3
Actual Temperature	22.9					

Table 4.25: Recorded Temperatures of Woven in RTDs at Hot Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1RW	36.8	52.4	49.7	55.1	131.0	76.1
W2RW	40.5	74.4	69.4	63.6	62.8	84.3
W3RW	41.3	59.5	64.0	59.5	65.2	126.5
Mean	39.5	62.1	61.0	59.4	86.3	95.6
Standard Deviation	2.4	11.2	10.2	4.3	38.7	27.1
Actual Temperature	37.0					

In comparison to the RTDs that were woven into the fabric structures, two of the three RTDs that were stitched onto the woven fabric samples were relatively more accurate in temperature measurement, as they were on average at least 9°C closer to the provided temperature than the woven in RTDs. Their accuracy was nowhere close to the accuracy obtained in the measurements made by the thermocouples, however, as the RTD that was stitched onto the third sample proved to be the most erratic of all of the temperature sensors, as it was on average at least 59°C off from the provided temperature (Tables 4.26 through 4.29). As for the integrity of the sensors, the RTD stitched onto the second sample was the only RTD to break during testing, and it broke before five washes were complete. However, it was the lack of accuracy in terms of temperature measurement for the RTDs stitched onto the woven fabrics that eliminated these sensors as a viable option, as the repeated disconnection from the electrical connectors prevented calibration from being maintained throughout the study.

Table 4.26: Difference of Recorded Temperature from Actual Temperature with Stitched on RTDs at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1RS	0.1	18.18924731	14.802151	0.90430108	16.7086022	55.4473118	17.691935
W2RS	0.2	30.1122449	14.186735	broken			14.832993
W3RS	0.3	78.69047619	77.438095	71.1238095	69.0190476	111.12381	67.949206

Table 4.27: Difference of Recorded Temperature from Actual Temperature with Stitched on RTDs at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
W1RS	0.3	26.59139785	21.173118	5.66989247	25.1387097	50.3774194	21.541756
W2RS	2.4	34.04897959	11.843878	broken			16.097619
W3RS	2.4	53.04285714	56.280952	66.0761905	66.7285714	110.085714	59.102381

Table 4.28: Recorded Temperatures of Stitched on RTDs at Room Temperature (in °C) in Comparison of Pre Wash to Launderings

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1RS	22.8	4.8	8.2	24.0	6.4	-32.4
W2RS	21.5	-6.6	8.4	broken		
W3RS	21.3	-54.9	-53.9	-48.2	-46.3	-88.2
Mean	21.9	-18.9	-12.4	-12.1	-20.0	-60.3
Standard Deviation	0.8	31.7	35.9	51.1	37.3	39.4
Actual Temperature	22.9					

Table 4.29: Recorded Temperatures of Stitched on RTDs at Hot Temperature (in °C) in Comparison of Pre Wash to Launderings

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
W1RS	36.8	11.2	16.3	31.2	12.0	-12.9
W2RS	40.5	4.1	26.1	broken		
W3RS	41.3	-15.8	-19.1	-29.2	-30.1	-73.0
Mean	39.5	-0.2	7.8	1.0	-9.1	-42.9
Standard Deviation	2.4	14.0	23.8	42.7	29.8	42.5
Actual Temperature	37.0					

Knitted Fabrics

The insulated thermocouples that were interlaced into the knitted fabric structure weren't as accurate as the thermocouples that were incorporated using differing methods before calibration, as they were on average more than 1°C off from the temperature that was provided (Tables 4.30 through 4.33). The interlaced insulated thermocouples also were more durable than the woven in thermocouples, as only the thermocouple in the first knit fabric fell out before testing, while all of the woven in thermocouples slipped out of the woven structure during the testing process. This ability to remain in the fabric sample was due to the bending of the thermocouples during the interlacing process, as the bending of the wires prevented the insulated thermocouples from freely moving within the knitted fabric structure.

Table 4.30: Difference of Recorded Temperature from Actual Temperature with Interlaced Insulated Thermocouples in Knit Samples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
K1IK	broken						
K2IK	0.2	0.2	0.4	0.8	0	0.3	0.3166667
K3IK	0.1	0.2	0.1	0.4	0.6	0.2	0.2666667

Table 4.31: Difference of Recorded Temperature from Actual Temperature with Interlaced Insulated Thermocouples in Knit Samples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
K1IK	broken						
K2IK	0.7	0.2	0.1	0.4	0.3	0.1	0.3
K3IK	1.2	0.3	0.1	0.5	0	0.3	0.4

Table 4.32: Recorded Temperatures of Interlaced Insulated Thermocouples in Knit Samples at Room Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
K1IK	broken					
K2IK	21.0	23.5	22.9	22.5	23.2	22.9
K3IK	21.3	23.9	23.3	23.2	22.6	23.1
Mean	21.2	23.7	23.1	22.9	22.9	23.0
Standard Deviation	0.2	0.3	0.3	0.5	0.4	0.1
Actual Temperaure	22.9					

Table 4.33: Recorded Temperatures of Interlaced Insulated Thermocouples in Knit Samples at Hot Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
K1IK	broken					
K2IK	36.8	37.8	37.4	36.3	36.5	36.4
K3IK	39.8	36.3	37.1	36.3	36.6	35.8
Mean	38.3	37.1	37.3	36.3	36.6	36.1
Standard Deviation	2.1	1.1	0.2	0.0	0.1	0.4
Actual Temperature	37.0					

Like the other thermocouples utilized in this research, the insulated thermocouples that had been stitched onto the knitted fabric were accurate in temperature measurement, as they were on average less than 1°C off from the actual temperature that was provided (Tables 4.34 through 4.37). The stitched on insulated thermocouples were also durable, as all of the thermocouples were able to withstand both the manufacturing process and the twenty washes encountered during the sensor testing process. This durability was due to the fact that the stitching was able to hold the insulated thermocouple and prevent movement, with the stitching acting as a better binder.

Table 4.34: Difference of Recorded Temperature from Actual Temperature with Stitched on Insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
K1IS	0.5	0.1	0	1	0.3	0.6	0.4166667
K2IS	0.2	0.9	0.1	0.7	0.1	0.2	0.3666667
K3IS	0.2	1	0.3	0.2	0.3	0.4	0.4

Table 4.35: Difference of Recorded Temperature from Actual Temperature with Stitched on Insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
K1IS	0.1	0.2	0.2	0.5	0.3	0.4	0.2833333
K2IS	0.3	0.4	0.3	0	0.2	0.2	0.2333333
K3IS	1.3	0.1	0.2	0.1	0.2	0	0.3166667

Table 4.36: Recorded Temperatures of Stitched on Insulated Thermocouples at Room Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
K1IS	21.0	23.5	23.2	21.9	22.9	24.2
K2IS	21.0	24.6	23.4	24.0	23.1	23.0
K3IS	21.6	24.7	23.5	22.6	22.9	22.9
Mean	21.2	24.3	23.4	22.8	23.0	23.4
Standard Deviation	0.3	0.7	0.2	1.1	0.1	0.7
Actual Temperature	22.9					

Table 4.37: Recorded Temperatures of Stitched on Insulated Thermocouples at Hot Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
K1IS	38.8	38.7	37.4	36.3	37.2	35.7
K2IS	37.2	38.0	37.6	36.7	36.6	36.5
K3IS	39.9	36.5	37.0	36.9	36.4	36.1
Mean	38.6	37.7	37.3	36.6	36.7	36.1
Standard Deviation	1.4	1.1	0.3	0.3	0.4	0.4
Actual Temperature	37.0					

When the un-insulated thermocouples that were interlaced into the knitted fabric were tested, the results were comparable to the insulated thermocouples that were interlaced into knitted fabric, as the low levels of variability show that the thermocouples were able to accurately record the temperature of their surroundings (Tables 4.38 through 4.41). The un-insulated thermocouples were able to withstand twenty washes, as the one broken thermocouple was due to the knitting process. The knitting action caused the soldered junction on K2UK to break due to bending of the soldering.

Table 4.38: Difference of Recorded Temperature from Actual Temperature with Interlaced Un-insulated Thermocouples in Knit Samples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
K1UK	0.3	0.2	0.4	0.1	0.2	0.3	0.25
K2UK	broken						
K3UK	0.1	0.6	0.1	0.3	0.1	0.3	0.25

Table 4.39: Difference of Recorded Temperature from Actual Temperature with Interlaced Un-insulated Thermocouples in Knit Samples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
K1UK	0.1	0.4	0.3	0.3	0	0.5	0.2666667
K2UK	broken						
K3UK	1.5	0.5	0.1	0.1	0.3	0.7	0.5333333

Table 4.40: Recorded Temperatures of Interlaced Un-insulated Thermocouples in Knit Samples at Room Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
K1UK	21.2	23.4	22.8	22.8	23.4	23.9
K2UK	broken					
K3UK	21.5	24.3	23.1	22.5	23.3	23.6
Mean	21.4	23.9	23.0	22.7	23.4	23.8
Standard Deviation	0.2	0.6	0.2	0.2	0.1	0.2
Actual Temperature	22.9					

Table 4.41: Recorded Temperatures of Interlaced Un-insulated Thermocouples in Knit Samples at Hot Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
K1UK	38.6	38.9	37.5	36.5	36.9	35.6
K2UK	broken					
K3UK	40.1	36.1	37.3	36.7	36.3	35.4
Mean	39.4	37.5	37.4	36.6	36.6	35.5
Standard Deviation	1.1	2.0	0.1	0.1	0.4	0.1
Actual Temperature	37.0					

When the un-insulated thermocouples that were stitched onto the knit fabrics were tested, the amount of variation was consistent with the variation encountered in the other thermocouples, as the un-insulated thermocouples were within 1°C of the actual temperature. The thermocouples were fragile, however, as K3US was broken before testing commenced due to the thermocouple wires moving during the stitching process, and K1US broke before five washes were complete after being tangled with a wire from another sample during hand washing (Tables 4.42 through 4.45).

Table 4.42: Difference of Recorded Temperature from Actual Temperature with Stitched on Un-insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
K1US	0.4	1.2	0.5	broken			0.7
K2US	0.2	0.4	0.3	0.1	0.3	0.3	0.2666667
K3US	broken						

Table 4.43: Difference of Recorded Temperature from Actual Temperature with Stitched on Un-insulated Thermocouples at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
K1US	0.1	0.4	0.4	broken			0.3
K2US	0.1	0.1	0.2	0.2	0.3	0.3	0.2
K3US	broken						

Table 4.44: Recorded Temperatures of Stitched on Un-insulated Thermocouples at Room Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
K1US	21.1	24.8	23.7	broken		
K2US	21.0	24.1	23.6	23.4	23.5	23.5
K3US	broken					
Mean	21.1	24.5	23.7	23.4	23.5	23.5
Standard Deviation	0.1	0.5	0.1			
Actual Temperature	22.9					

Table 4.45: Recorded Temperatures of Stitched on Un-insulated Thermocouples at Hot Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
K1US	38.6	38.1	36.8	broken		
K2US	37.6	37.7	37.5	36.5	37.1	36.6
K3US	broken					
Mean	38.1	37.9	37.2	36.5	37.1	36.6
Standard Deviation	0.7	0.3	0.5			
Actual Temperature	37.0					

When compared to the RTDs placed within the woven samples, the RTDs that have been stitched onto the knit samples were closest to the actual temperature, as all of the stitched on RTDs recorded temperatures that were within 20°C of the actual temperature, which is much better in comparison to other RTDs, but still inaccurate and unusable when compared to the thermocouples (Tables 4.46 through 4.49). As for the construction of the stitched on RTDs, there were no breaks during the testing, as all of the sensors were able to record temperatures after twenty washes, which is comparable to the other RTDs used during testing. While the stitched on RTDs were able to generate readings, they were not a viable temperature sensing device, as the erratic measurements created did not indicate a reliable temperature sensor, as disconnecting from the electrical connectors eliminated the calibration.

Table 4.46: Difference of Recorded Temperature from Actual Temperature with Stitched on RTDs at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
K1RS	0.3	5.943023256	5.8343023	11.6709302	14.005814	43.9116279	13.61095
K2RS	0.2	9.377202073	13.662176	13.5777202	6.24559585	21.3715026	10.739033
K3RS	0.1	17.79196787	6.7248996	6.17710843	6.20763052	31.4321285	11.405622

Table 4.47: Difference of Recorded Temperature from Actual Temperature with Stitched on RTDs at Room Temperature (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes	Average
K1RS	0	3.252325581	3.3313953	13.3616279	9.39186047	15.2052326	7.4237403
K2RS	0.2	6.456476684	5.1518135	11.1569948	3.03367876	29.4041451	9.2338515
K3RS	1.3	20.71606426	11.709639	12.7875502	10.7401606	50.8827309	18.022691

Table 4.48: Recorded Temperatures of Stitched on RTDs at Room Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
K1RS	21.2	29.5	29.0	11.2	9.2	-20.3
K2RS	21.0	33.1	37.0	36.9	29.4	1.8
K3RS	21.5	5.9	16.5	16.6	17.0	-8.1
Mean	21.2	22.8	27.5	21.6	18.5	-8.9
Standard Deviation	0.3	14.8	10.3	13.5	10.2	11.1
Actual Temperature	22.9					

Table 4.49: Recorded Temperatures of Stitched on RTDs at Hot Temperature in Comparison of Pre Wash to Launderings (in °C)

	Pre Wash	1 Wash	3 Washes	5 Washes	10 Washes	20 Washes
K1RS	38.7	41.8	40.5	23.4	27.5	20.9
K2RS	37.3	44.1	42.5	47.9	39.8	6.9
K3RS	39.9	15.9	25.5	24.0	25.9	-14.8
Mean	38.6	33.9	36.2	31.8	31.1	4.3
Standard Deviation	1.3	15.6	9.3	13.9	7.6	18.0
Actual Temperature	37.0					

CHAPTER 5 - Conclusions

The purpose of this study was to determine the effectiveness of weaving and knit-weaving thermocouples and RTDs into a textile-based structure, as well as examining how the sensors were able to withstand multiple launderings while still being able to measure temperature accurately. It is through this research that the eventual goal of creating a temperature sensing garment would be achieved, as the information gathered during this study would determine what type of sensor and incorporation method would be best for making a temperature sensing garment. The research questions posed for this study concern the effectiveness of the sensor types after incorporation, as well as their ability to withstand multiple hand washings.

Thermocouples

Insulated Thermocouples Woven in and Stitched onto Woven Fabric Structures

The insulated thermocouple's wide range of movement for both the stitched on and woven in thermocouples made it possible to adjust the position of the temperature sensor with little stress applied to both the thermocouple and the woven fabric, with the woven in thermocouples having a greater range of movement. However, this wide range of movement led to all of the thermocouples slipping out of the woven fabric and one insulated thermocouple was able to slip out of the stitching with minimal force exerted by moving the sample for testing. The weave and stitch structure were not tight enough, as multiple insulated thermocouples fell out of the woven fabric after multiple washes. This increased movement helped answer both research questions posed, as the slippage of the thermocouples out of the fabric structure made it impossible for the temperature sensors to make accurate measurements while staying inside the fabric structure, with the hand washing exacerbating the problem by promoting slippage due to increased movement of the sensors. In order to use this type of implementation for temperature measurement, the resulting fabric sample would be best suited for situations that limited the movement of the thermocouple wires within the fabric structure.

For future research with this implementation method, there are several ways in which insulated thermocouples that have been woven into the fabric structure can be improved. In order to prevent slippage of the thermocouples out of the structure, a tighter weave or stitch pattern, as well as a higher thread count, could be employed in order to retain the thermocouple within the fabric structure, as well as to make a fabric sample that is more similar to what would actually be worn close to the body. The size of the thermocouple being utilized could also be analyzed, with different gauges examined to see if smaller or larger thermocouples would be effective after multiple washes.

Un-insulated Thermocouples Woven in and Stitched onto Fabric Structures

One of the major differences between the un-insulated thermocouples that have been incorporated into the woven fabric structure and the woven in and stitched on insulated thermocouples was the diminished ability for the un-insulated thermocouple wires to be moved within the fabric structure, as the woven and stitched pattern was able to hold the thermocouples in a more rigid structure. While it was possible to make minor adjustments to the position of the woven in un-insulated thermocouples, it was difficult to alter the position of the stitched on un-insulated thermocouples without breaking the stitching. This lack of movement helped answer the first research question posed, as the ability for the sensors to measure accurately illustrate how this method was effective in making an accurate temperature sensing fabric The movement ability of the woven in thermocouples may have caused the soldered junctions in two of the woven samples to be subjected to sufficient stress to break the soldering, separating the thermocouples and breaking them during the hand washing process. The stitched on thermocouples did not exhibit such behavior, and it is possibly because of the lack of the movement ability that all of the stitched on thermocouples were able to withstand 20 washes, helping answer the second research question which was based on the ability of the sensors to measure temperature after multiple hand washings. If this implementation method was to be used in temperature measurement in the future, it would be best suited for situations that limit the stress that is placed upon the soldered junction point, such as placement on areas of the body that are not prone to bending and flexing, such as the right scapula or the forehead.

For future research, it would be beneficial to vary the distance that is placed between the un-insulated thermocouple wires to isolate the effects of the stress that is placed onto the soldered junction. The distance may play a part in the breakage of the thermocouples. The soldering that is used to form the sensing junction of the thermocouple could also be enhanced, as there are multiple types of solder that can be used in an experiment to ensure that the thermocouples can perform after multiple washes.

Insulated Thermocouples Interlaced and Stitched onto Knitted Fabric Structures

The insulated thermocouples that were interlaced into the knitted fabrics have a limited range of movement, as the interlacing caused the wires to be bent to the point where if an attempt to move the thermocouple was made, the thermocouple would snag on a yarn as opposed to moving. For the insulated thermocouples that were stitched onto the knitted structure, the stitch pattern held the thermocouple in place more rigidly in comparison to the stitch pattern on the woven fabric. The more rigid placement helped prevent the insulated thermocouples from slipping out of the structure, as only one fell out of the fabric immediately after the sample was completed. In answering the research questions, the insulated thermocouples that were interlaced or stitched onto the knitted fabric structures were able to be an accurate temperature sensor when placed in the fabric sample, as well as the laundering having little effect on the accuracy of the sensors. These two sensor incorporation methods were the best in terms of creating an electronic textile fabric, as the knit structure provided a more flexible fabric, with the sensors less prone to breaking or slipping out than other incorporation methods.

Areas of future research that could be conducted include changing the gauge of the thermocouple being used for the knitting process, as the kinked thermocouples would be noticeably rough for the wearer. The knitting operation could also be modified in the future, as the process places the thermocouples under a stress that causes them to kink heavily, with the kinks becoming extremely difficult to remove without taking the thermocouple out of the fabric structure.

Un-insulated Thermocouples Interlaced and Stitched onto Knitted Fabric Structures

The same issues that were present with the un-insulated thermocouples in the woven samples are present in the knit samples. Two of the thermocouples broke before testing began, with another breaking before five washes. The knitting process was harsh enough to break the solder junction outright, while the solder on two of the stitched on thermocouples broke when the thermocouple was being adjusted in order to obtain an accurate measurement. The flexibility of the structure was too much for the un-insulated thermocouples, as attempting to adjust the thermocouple presented the risk of breaking the soldering with little effort. In answering the research questions posed, these sensors were accurate when placed into the knitted fabric as long as the sensors did not break during the incorporation process, and when laundering was introduced, there was no additional breakage caused by hand washing the samples. In terms of use for an electronic textile, this incorporation method would be the least effective in terms of thermocouple use, as they are prone to breaking too easily, and the bending of the knit structure would cause the soldering to break due to the additional stress.

Areas of future research that could be examined include the altering of the knitting process to relieve some of the stress that is placed on the soldered junctions of the thermocouples while they are being machine knitted. The stitching on of thermocouples could also be examined with the use of undershirts, as the thermocouples could be stitched onto the side of the fabric that will come in contact with the body, with the wearing of the garment possible, as well as applying multiple hand washes to measure laundering characteristics.

RTDs

In terms of incorporating RTDs into fabric structure, it is not viable to implement RTDs within a knit structure, as wires that are fine in gauge are not able to withstand the stresses caused by the knitting process. While that process was able to destroy all of the copper wires, all of the other incorporation methods used helped produce a temperature sensor that can withstand multiple washes, as only one of the RTD wires broke during the washing procedure. It is the variability of the RTDs that have been incorporated in both woven and knitted fabrics that poses a major flaw, as none of the measurements generated were close to being accurate, and as these sensors will be used to measure human body temperature, the difference of 1°C is crucial, helping answer the first research question that was posed. The most likely cause of the wide variation was the disconnection of the RTD wires from the processing unit to wash the samples, as multiple disconnections and reconnections can generate values that are drastically different than expected. There was no measureable effect of temperature variation due to the hand washing process itself, which addresses the second research question posed.

For future research into RTDs, one major improvement would be the creation of an electrical connector that would be able to withstand contact with water, as the connectors that were used would corrode if placed in water. This advancement would allow the RTD to be connected at all times, while still allowing the fabric being used for sensor measurements to be washed, extending the lifespan of the electronic textile. The type of wire used as an RTD could also be changed, as a platinum wire would serve as a suitable RTD, and holds a major advantage over copper wires in that the resistance generated in platinum wire can be measured in hundreds of ohms, while the resistance recorded in copper wires is less than one ohm. This difference in resistance would minimize the effects of noise caused by the temperature measuring process, as well as minimize the effects of variation due to disconnecting the wires while washing the fabrics. However, the major disadvantage of using platinum would be the cost of the material, as it is a much more expensive material in comparison to copper.

Summary

Based on the results obtained in this study, many conclusions were made about the construction of a fabric that would be able to measure the skin temperature of the wearer. In terms of accuracy, it would be necessary to use thermocouples as the temperature sensing device, as the RTDs lacked the accuracy required to be used as a temperature sensor due to loss of calibration due to multiple disconnections. Insulated thermocouples that were either stitched on or interlaced into a knitted structure would be best to make a temperature sensing garment, as this incorporation method is best in preventing the thermocouples from slipping out of the fabric. It would be inadvisable to use un-insulated thermocouples, as the lack of insulation on the thermocouple wires makes it much more likely for the thermocouple to break, rendering the temperature sensor useless until the soldering junction has been soldered again.

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