Resistively Heated Fabrics for Use in Wearable Therapeutic Devices

by

Aria H. Reynolds

Submitted to the Department of
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ABSTRACT

Wearable technology is an emerging multidisciplinary field. When designing wearables, one must draw upon an understanding of: the available soft materials; the motion of the body; as well as comfort, fashion, and social implications. There is a lot of current research exploring manufacturing processes and user's needs for wearable products, but there are not many products available on the market. Medicine is one field that can benefit from the use of these design principles, however. Patients that require constant care or treatment for chronic diseases have few choices available to them in terms of medical devices. Many available medical products focus only on their functionality, and neglect fashion, convenience, and comfort.

Arthritis and other rheumatic diseases are the cause of most disabilities in the United States, and cause chronic pain in joints all over the body. There are few non-invasive treatments available to patients suffering with these diseases, so this project seeks to fill that gap in the market. The Selectively Heated Therapeutic Sweater allows the patient freedom to choose where and when heat treatment is applied to their joints throughout the day. It also takes into consideration their right to privacy and makes the treatment as unobtrusive to daily life as possible.

Conductive fabric was used as a resistive heater powered by low-profile button batteries. The connections of this battery pack were made by using fabric snaps which allow for temporary placement and easy removal for washing. The sweater functioned as anticipated, but could have been improved through the use of soft battery holders and conductive threads.

Thesis Supervisor: David Wallace
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1 Introduction

When the phrase "product development" is used it is usually associated with toasters or phones purchased at a local mega mart. But what if current technology could be integrated into something that affects us on a closer, more fundamental level—our clothing? Garments represent different things to different people, but provide an engineer with new challenges, design considerations, and a different canvas with which to work. Wearable products are becoming an increasingly large market segment, and are being developed by many people with a wide variety of backgrounds. Given the interdisciplinary nature of the subject, it is helpful to define the terms which describe the current state of design and innovation.

A wearable product seems to be anything that is worn on the body. However, as devices become smaller and technology advances, it becomes apparent that the lines between wearable and portable are blurred. Is a cell phone considered a wearable product, as it appears glued to many people's ears? On the other extreme, are implanted devices wearable or do we assume them to just be part of our bodies? The broad definition we will be using in order to remedy this confusion is as follows: A wearable product is a personal item on or in the body used on a daily basis to perform a specific task or represent us as individuals.

Wearable technology is another phrase that is being used to describe the cross-over between fashion and electronics. It is used to describe any garments or devices that contain sensors, motors, microprocessors, batteries, conductive materials, soft circuitry, cameras, or any other number of electronic components. While some of the devices that fall under this category can be thought of as wearable computers, it is not necessary that the garment have a computer's functionality. Sabine Seymour expresses her use of wearable technology instead as "the immediate interface to the environment and thus [is] a constant transmitter and receiver of emotions, experiences, and meaning."[1] In addition to this interpretation of the function of the products, we also stipulate that while these devices may perform other tasks, they must still recognize the human form as its context, and conform to wearability, functionality, operational, and aesthetic standards.

While these definitions allow us to understand the discourse within the realm of wearable design, they do not encompass the entire field. We recognize that there are many different objects worn on the body which do not fit the standards of function or wearability laid out here. There are garments being developed which are meant to explore and experiment with the cultural significance of clothing, or are meant to express the designer's point of view on various issues, and while these garments have their own significance as art pieces, they will not be discussed here.

1.1 Purpose of the Study

The history of wearable products is a long one, starting with the use of skins as clothing more than 100,000 years ago, and continuing on with the development of equipment and techniques to create cloth around 8500 years ago,[2] the use of crystals for eyeglasses, and the invention of the watch.[3] Clothing is so closely related to who we are as individuals however, that with each new evolution of technology a change in culture, sense of self, quality of life, human capability, and economy also occurs. It is because of this close relation that wearable products are so interesting, and an area which can have extremely important societal implications. Wearable products also span many different industries including fashion, art, health care, computer, energy, recreation, and manufacturing.

Currently, there is the desire to discover new ways to integrate technology into soft materials, and much of the experimentation is being done by groups at various universities. These prototypes serve as an excellent foundation on which marketable products can be developed. The key difference remains that the original experiments focus on the capabilities of using a technology in the context of the human body, whereas for full scale production manufacturing processes, price, user interface, life span, ergonomics, and safety must be considered to be successful. This study aims to bridge the gap between these two levels of development and address the concerns of scaling up production. It will also serve as documentation of the design process and the considerations that must be made in order to have a successful finished wearable product.

In addition this study addresses a need in the market for unobtrusive, cost effective, and capable medical devices. Given the amount of advanced technology that has been developed for the health care industry, the ability to have portable and convenient health care is not in question. However, many devices have not been designed to work with the patient's body, be discrete, or comfortable to wear for extended periods of time. The Selectively Heated Therapeutic Sweater seeks to combine the need for health care with the design process for wearable technology, giving the user a controllable, fashionable, and comfortable method of treatment without disclosing its necessity to an outside observer.

Finally, arthritis and rheumatism are the most prevalent disabling diseases in the United States, with over 46 million adults currently diagnosed.[4] It is a chronic, debilitating disease that causes pain, swelling, and stiffness in the joints and supporting muscles. These symptoms often lead to loss of range of motion or ability to perform simple tasks such as climbing stairs or dressing oneself.[5] The application of heat for long periods of time can help relieve some of the pains involved and with therapy, can increase the range of motion in joints. Also, when paired with cold, it allows for a customizable treatment plan based on the patient's preferences. The Heated Sweater, as shown in Figure 1, aims to be a cheap, readily available treatment option for many of the sufferers in order to aid with pain management and daily activity.

Figure 1: Inside of Therapeutic Heated Sweater with removable battery pack.

1.2 Current Wearable Medical Devices

Personal health care can be approached from two different standpoints: preventative care and treatment. Patients can improve their lives by addressing both of these areas with the use of customized clothing. By far the most common method of preventing injury or diagnosing an illness with wearable technology is by integrating strategically located sensors. Products currently on the market mainly target athletes and include NuMetrex clothing with built-in heart rate monitors, and Adidas' miCoach heart rate, stride, and calorie burn sensors.[6] However, there are studies focused on integrating different types of sensors into everyday clothing that will be suitable for a larger section of the population. One of these studies focuses on creating a small EMG sensor which would be embroidered onto clothing rather than strapped around the chest.[7] Others discuss the possibility of monitoring vitals of an unborn child, the position of the body, analyzing motion, or detecting stress.

Medical devices intended to treat a problem while being worn afford the patient greater freedom and control over their bodies. A wearable, although bulky, defibrillator deemed "The LifeVest" allows sufferers of sudden cardiac arrest the opportunity to live normally outside of the hospital with the assurance that they will receive the same care.[8] Other treatment products include clothing specifically designed with the needs of autistic children in mind. The Beagle Scarf is a hooded vest that incorporates music, different textures, scents, and the capability to create pressure around one's torso to stimulate the senses in order for the child to feel relief.[9] There is a broad range of conditions currently being treated by wearable medical devices, but this is an expanding field due to the advancements in nanotechnology, "smart" materials, and batteries and renewable energy.

1.3 Product Design Process

The methods used in order to generate ideas, solve problems, prototype, and manufacture a product may vary from person to person, but the steps of the creative process can be outlined in order to guide the process. A well documented progression through the steps can also aid in others following the logic of the designer and prove that well informed decisions were made.

The first step in the process is to understand the problem the product is designed to solve and the actions it will ultimately perform. By breaking down the problem into several different parts, the foundation for modular design is laid, so that changes in one module do not affect the work done on the entire product. Several ideas are then generated for each module and the mechanisms and principles they will use are defined. In order to determine which ideas suit the requirements the best, mechanical analysis or experiments must be performed. When the options have been narrowed down and a starting place has been developed, benchmarking is a good idea. Looking at other products on the market allows the designer to better understand the customer and the current state of the relevant technology. Other research should also be performed in support of any design decisions that were made or in support of any analysis. Finally any problems or risks in the design that can be anticipated should be noted and strategies to overcome them should be implemented. At this phase the actual construction can begin and any problems encountered there will initiate another iteration of the entire process until a satisfactory product is developed.[10]

1.4 Selectively Heated Therapeutic Sweater

As an exploration into the design process used for wearable medical devices, the idea of addressing the needs of those with arthritis or chronic muscle pain was developed. Having family members who cope with arthritis on a daily basis provided me with a knowledge base of conventional treatments and indicated applications, which I then verified with relevant medical literature. It was determined that extended periods of heat treatment serve as an effective way to improve circulation, relax muscles, and aid in ridding the body of the pain associated with arthritis.[11] With this information the idea for an unobtrusive garment that could provide constant treatment was developed. A long sleeve sweater would cover the shoulders, elbows, wrists, and spine, where many problems can arise.

The most important aspect of the design is that the heating element's location can be selectively applied, relocated, or removed, depending on the user's needs. This was accomplished by integrating fabric snaps for the electrical and mechanical connections. Button batteries were chosen in order to provide a flat profile for the element on the inside of the clothing. A circuit was created with thin wire and conductive fabric for the pack to be as flexible and comfortable as possible. The specific shape and placement of the heat pack was determined by examining ergonomic data and maintaining unobstructed range of motion.

2 Background

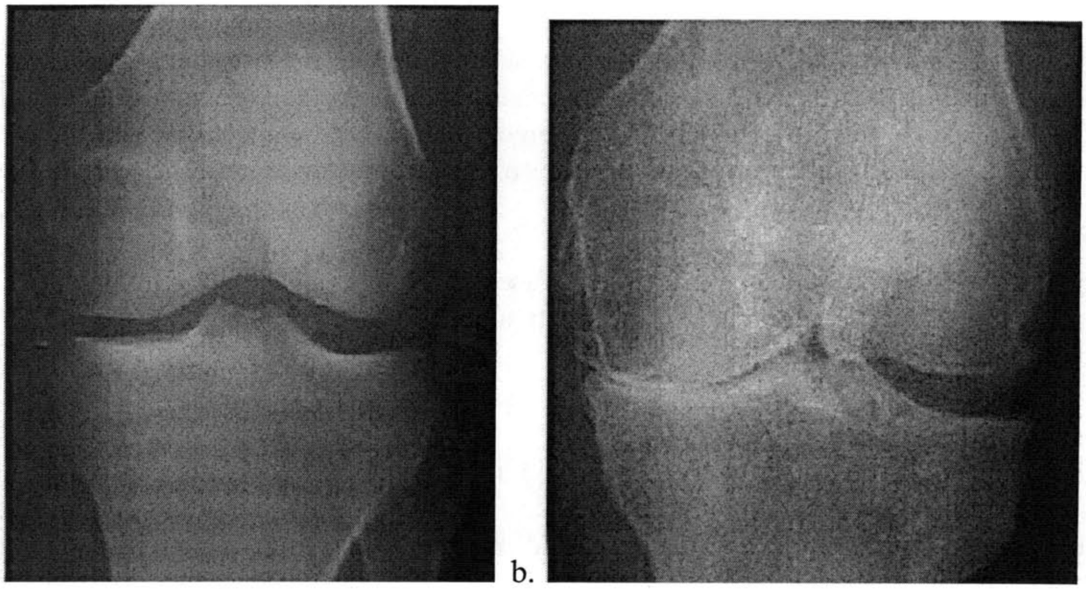
The design of a wearable medical device is the culmination of many different areas of research. In order to understand the end user, their needs must be explored and the medical relevance of the device ensured. Once the governing physical properties of the product are understood one can analyze what is happening in the system and make informed design decisions. Finally, the appropriate materials must be selected which will suit both the needs of the user and the garment parameters.

2.1 Arthritis

Arthritis is a chronic illness that affects over 46 million adults in the United States, as well as 300,000 children. It is characterized by swelling and inflammation of the joint linings and cartilage. Every year about 750,000 people must be hospitalized due to complications or severe symptoms of the disease. While arthritis can affect people of all ages, it is primarily a geriatric affliction, and one that may worsen with age. Women are also three times more likely to develop some form of arthritis than men. There are many different types of arthritis, but the most common ones are osteoarthritis, rheumatoid arthritis, septic arthritis, juvenile idiopathic arthritis, and ankylosing spondylitis.

2.1.1 Types of Arthritic Diseases

Osteoarthritis affects weight bearing joints such as the spine, hips, and knees. It is caused by daily wear of the cartilage which leads to worsening joint pain as one ages. An x-ray of an osteoarthritic knee, Figure 2, shows the lack of cushioning and subsequent bone wear caused by the lack of cartilage. It is not curable but further wear can be prevented or it may be helped with joint replacement surgery.



a. b.

Figure 2: (a) Non-arthritic knee (b) Osteoarthritic knee showing severe joint space narrowing and bone spurs, indicating advanced wear.[12]

Rheumatoid arthritis is brought about when the body's immune system attacks its tissues. The disease attacks many areas of the body, but primarily results in the damage of cartilage, joint lining, and the surrounding bone. Primarily the hands, wrists, elbows, and knees are affected and will begin to deform a few years after diagnosis, as shown in Figure 3. There is no cure for this form arthritis, and it will cause progressive deterioration with time.

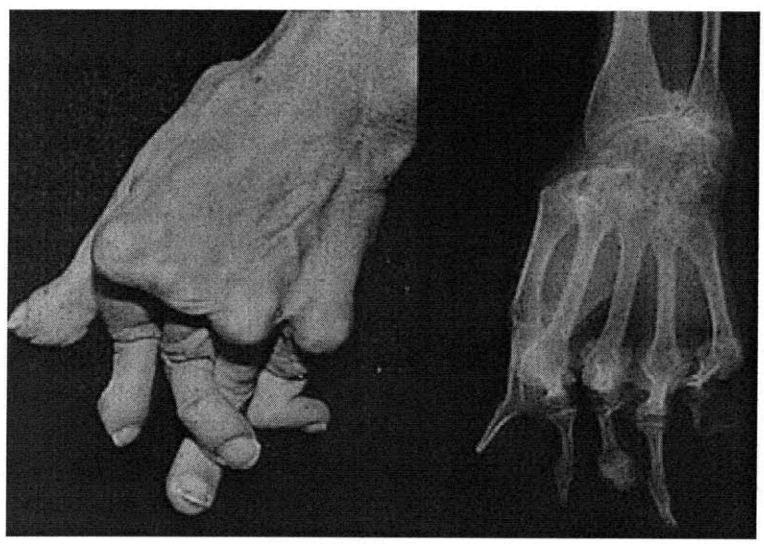


Figure 3: Advanced hand deformation including ulnar deviation and carpal dislocation.[13]

Juvenile idiopathic arthritis has no known cause, but is diagnosed in children under the age of 16. This disease can cause flu-like symptoms, but is identified by the swelling of the knee, ankle, wrist, hands, and feet. If untreated, it can lead to joint deformations, stunted growth, and even blindness.

Ankylosing spondylitis is a chronic arthritis and autoimmune disease that primarily affects the spine and hips. This arthritic disease affects men more often than women, unlike most others. Eventually it can lead to the fusion of vertebrae, but presents with fatigue, inflammation, and osteoporosis. There is no cure for this disease so the chronic severe joint pain and inflammation progressively get worse.

Septic arthritis is caused when bacteria, viruses, or fungi, spread to a joint and cause the accumulation of pus in the area. This is a treatable form of arthritis that can be cured with antibiotics and joint aspiration.[14]

2.1.2 Arthritis Treatments

As the many variations of arthritis are chronic and incurable, treatments can only manage the pain and symptoms associated with the disease. For osteoarthritis, the progression of the disease can be stopped with weight loss, exercise, and using only low-impact activities. For the other more serious forms of arthritis anti-inflammatory medications, physical therapy, and surgery are generally prescribed to the patients. Immune altering medications such as cortisone can also be prescribed which function to protect the body against its own antibodies. In addition the deterioration of the joints from inflammation can be slowed with glucosamine supplements.[15]

Pain in all arthritis patients is managed with over the counter medications such as aspirin or ibuprofen. The combination of heat and cold therapy also aids in the reduction of pain. The application of cold can reduce inflammation and swelling while numbing the area. However, in most cases the muscles surrounding the joints fatigue and are irritated by the inflammation as well. Therefore pairing heat therapy with cold relaxes muscles, increases circulation, and can heighten the threshold for pain. It is also very important for recovering from morning stiffness and regaining joint mobility. In fact, for acute back pain eight hours of continuous heat application at 40°C was shown to be more effective than either ibuprofen or acetaminophen.[16]

2.2 Resistive Heating

When energy is transformed from an electrical form into a thermal form, it is called resistive heating, also known as Joule or Ohmic heating. Resistivity is an extensive property of every material that has units of ohm-meters. Therefore it depends on the length and cross sectional area of the material through which the current flows. Metals are also subject to a change in properties with a change in operating temperature.

The production of heat through resistive heating begins with the electrical properties of the system, described by Ohm's Law:

$$V = I \cdot R, \tag{1}$$

where V is voltage, I is current, and R is resistance. The power produced by the circuit is then defined by Joule's Law:

$$P = V \cdot I = I^2 \cdot R. \tag{2}$$

In order to take this information and make it useful in a thermal setting, we know that the power will be in the units of watts, or a rate of energy transfer, which is equivalent to that of heat flux in a system. Therefore we know that

$$\dot{Q} = I^2 \cdot R . \tag{3}$$

With this equation we can calculate the amount of heat being produced by any electrical system assuming that we know how to write Ohm's Law.[17]

2.2.1 Heat Transfer

The methods of heat transfer are conduction, convection, and radiation. Here we will consider the effects of conduction and convection. Conduction is defined as heat transfer through materials that are in physical contact with one another. A temperature gradient across the material will cause the heat to move from an area of high temperature to low temperature in order to achieve equilibrium. The rate at which the heat flows depends on the thermal conductivity of the material, *k*, the distance traveled, *x*, and the difference in temperature, *T*, over that length. As it is useful to describe the conduction as heat flux per unit area, the following equation is used:

$$\frac{\dot{Q}}{A} = \frac{k \cdot (T_2 - T_1)}{x} . \tag{4}$$

The thermal conductivity, *k*, is an experimentally found material property that depends on the material's atomic structure and its temperature. Therefore the same material with different crystalline structures or operating temperatures will have a different behavior. When considering the conduction across a composite structure, the conductivities of each material can be modeled as resistors in series. Resistivity is the inverse of conductivity, so its equation is:

$$R = \frac{x}{k} . \tag{5}$$

For resistors in series the resistances add together resulting in:

$$R_1 + R_2 = \frac{x_1}{k_1} + \frac{x_2}{k_2} = \frac{k_1 x_1 + k_2 x_2}{k_1 k_2} . \tag{6}$$

This new equivalent resistance can then be plugged into Equation 4 and calculated as before. However, the previous two equations can only be used when assuming that the heat is traveling through the same cross-sectional area of each material.

Convection is when heat is transferred through a fluid. When the fluid flow is caused by an external source not related to the heating process, it is called forced convection. Alternatively, the change in temperature can cause changes in the fluid's buoyancy which leads to bulk motion of the fluid. This is called free or natural convection. However, all heat transfer through convection is described by:

$$\frac{\dot{Q}}{A} = h \cdot (T_2 - T_1) , \tag{7}$$

where *h* is the heat transfer coefficient, T_1 and T_2 are the temperatures of the fluid and the surface, respectively, and *A* is the area over which the heat transfer is taking place. The heat transfer coefficient is the variable which takes into account the differences between forced and natural convection, fluid type, and geometry. For forced convection, *h* is found with the relation:

$$h = \frac{k \cdot Nu}{D} , \tag{8}$$

where k is the thermal conductivity of the fluid, Nu is the Nusselt number, and D is the hydraulic or characteristic diameter. The Nusselt number takes into account the turbulence of the flow, the fluid's diffusivity, and the geometry. The heat transfer coefficient over different materials or fluids, like the thermal conductivity, can be treated as a series of resistors. Because of this correlation, we can combine the coefficients for the conduction and convection heat flux equations. For example, if the heat traveled through a material via conduction and then was transferred to the air via convection, the heat transfer equation would be:

$$\frac{\dot{Q}}{A} = \frac{(T_1 - T_2)}{\frac{1}{h} + \frac{x}{A}} \quad (9)$$

Together with Equation 4, this equation describes the physical situation of having heat generated in a material and transferred both to the skin and to the surrounding air. Knowing which temperatures each surface is at and the constituent materials is enough to calculate the generated heat flux and use Equation 3 to find the required current and voltage to achieve it.[18]

2.3 Soft Electronics Materials

Wearable products are unique because they must be comfortable, flexible, and fashionable. Therefore the materials used must be functional and reliable while also interfacing well with the human form. Many of the electronic components, such as LEDs, batteries, or micromotors cannot be replaced, but as fashionable technology gains popularity, more materials are becoming available. These new materials include conductive fabrics, threads, and yarns, as well as thermochromic inks, electroluminescent embroidery thread, shape memory alloys, impact hardening fluid, and stretchable switches.

Conductive soft materials are the easiest way to complete circuits and create wearable technology. There are many different types of conductive fabrics, threads, and yarns that use different types of metals and manufacturing processes. The simplest yarns are simply a stainless steel core wrapped in either silk, cotton, or wool fiber, such as the one in Figure 4 from Habu Textiles.[19]

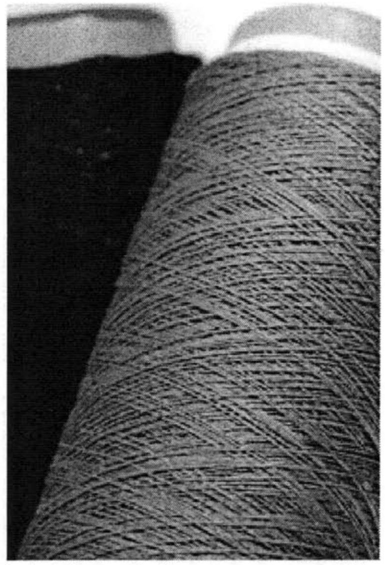


Figure 4: Silk-wrapped stainless steel core yarn used for knitting and weaving.

This type of yarn was originally made to be used in an oil filter so it is stiffer and has a memory that may not be desirable for some wearables. Other conductive yarns are manufactured by spinning metal filaments together with the fiber in order to create a softer yarn that has the characteristics of regular textiles. The yarn shown in Figure 5 was spun in this manner and consequently also has an interesting material property: the resistance of the yarn decreases when it is in tension. The high Poisson's ratio of the strand causes the diameter to shrink when in tension, allowing better contact among the steel filaments. The changing resistance makes this a useful material for a stretch or pressure sensor.[20]

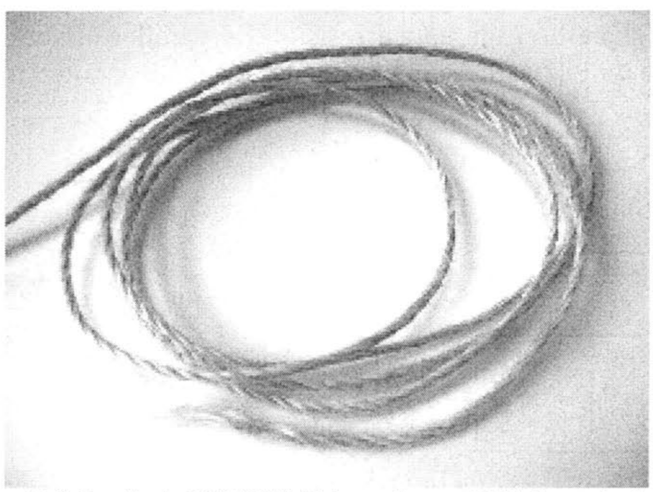


Figure 5: Schoeller's 10/3 80% Polyurethane, 20% Inox steel yarn.

A new process is currently being developed at the Institute of Textiles and Clothing at Hong Kong Polytechnic University to chemically deposit metal particles onto a cotton yarn structure. The researchers grew polyelectrolyte brushes directly onto the cotton fibers, and then used electroless deposition to adhere the metal to the surface. The result is a durable product that can withstand contact with air, rubbing, bending, stretching, and washing while maintaining the original conductive properties.[21]

Fabrics are made from fine woven conductive yarns and therefore maintain most of their material properties. Most are able to be cut and sewn like regular fabric, but also are able to shield against electric fields, radio waves, and static discharge. Examples of these textiles include ones made with silver, stainless steel, nickel, copper, and carbon fibers, as shown in Figure 6.[22]

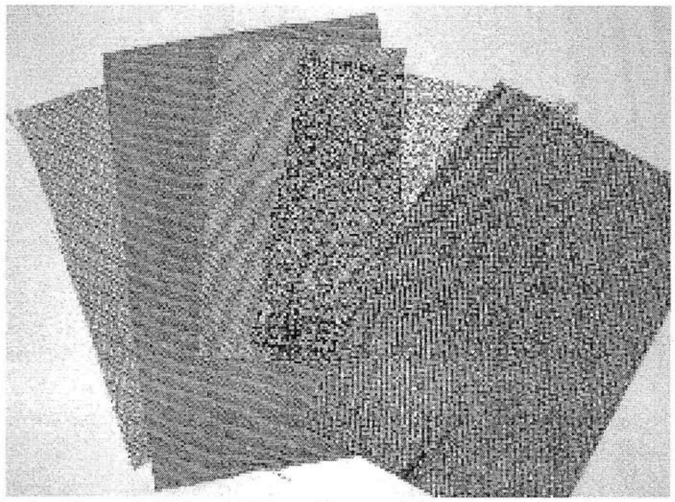
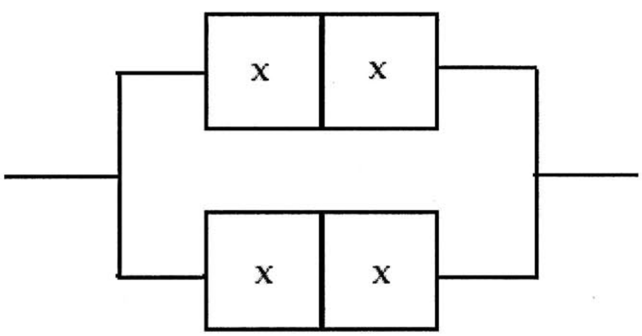


Figure 6: Conductive fabrics (from left to right): cotton and bamboo with silver, cotton with stainless steel, polyester taffeta with copper, stainless steel mesh, polyester with nickel.

As opposed to typical wire-like conductors and resistors, fabrics are composed of several strands perpendicular to each other. The current can then travel along all of the strands that span the two connection points. Whereas the resistance in wires has units of ohms/meter, the resistance along these fabrics has units of ohms/square. The strands act as resistors in parallel, distributing the current among them. Therefore, the added resistors in parallel offset any additional length so that a square of any size will have the same resistance, as demonstrated in Figure 7.



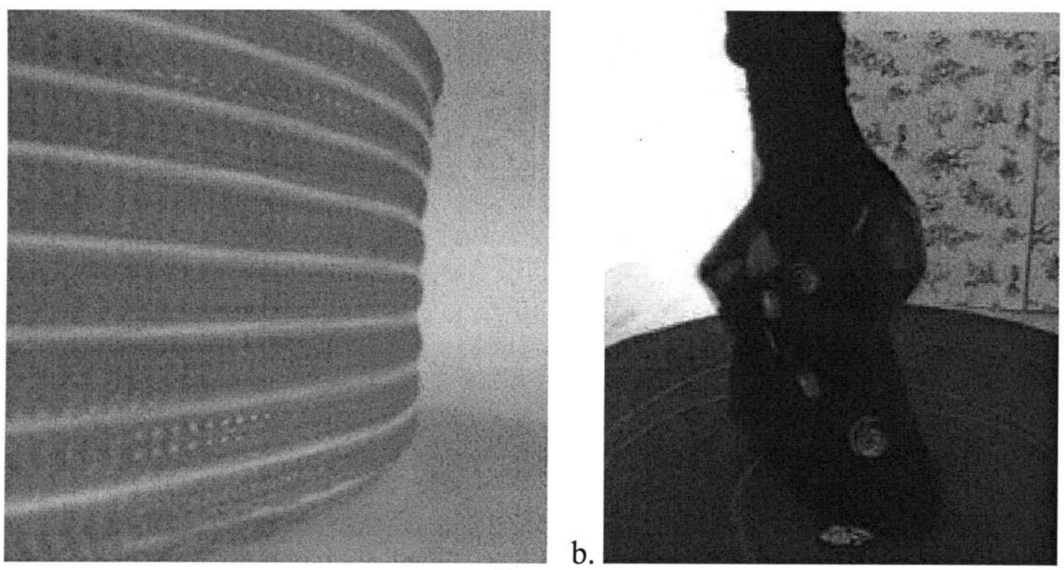
$$R_{sheet} = \frac{R_1 R_2}{R_1 + R_2} = \frac{2x \cdot 2x}{2x + 2x} = x$$

Figure 7: Sheet resistance as resistors in series and parallel, resulting in units of ohms/square.

Other materials typically used for garments can either have passive or active technological aspects. Thermochromic inks change colors at a specific temperature point. Designs may appear or the color may disappear with the application of heat, providing a passive technological addition. The dress shown in Figure 8 changes from white to an orange pattern with body heat, hot weather, or sunlight.[23]

Figure 8: Chiffon dress with thermochromic ink patterning.

On the other hand, electroluminescent thread and wires can be used to embellish fabrics so that the wearer has control over how their garment appears to others. Figure 9 shows two examples of active patterning of garments not possible with normal soft materials. LEDs, electroluminescent wires, sensors, actuators, and other electronic devices can be powered with solar panels integrated into the surfaces of clothing.



a. b.

Figure 9: (a) Electroluminescent wires in fabric tape[24] (b) Electroluminscent embroidery on a black dress.[25]

While electronics are most often composed of the standard wires, circuit boards, and batteries, the materials used in wearable technology must accomplish several tasks. They must be flexible, durable, and cheap enough to be worn only for a season. Familiarity with the materials available allows the designer to break away from traditional technology and implement new ideas in the clothing industry.

3 Benchmarking

Benchmarking is an important aspect of the product design process. It allows the designer to gain insight into the current state of technology, the customer, and the market. Looking at the products currently for sale, we can understand how the technology is being received and what demand there is for further development. Then, analyzing ongoing research in the field shows which products are likely to be designed next, and what advancements are being made in implementation. We will be looking at examples of wearable medical products in order to understand the state of the medical device industry and the uses for existing technology.

3.1 Medical Products on the Market

Most medical devices on the market are invasive devices that treat chronic diseases. Because these diseases are a part of everyday life, the products used to treat them must be extremely reliable without interfering with daily activities. Insulet's Omnipod insulin pump is an example of a minimally invasive product that has taken the customer into consideration. The pump is wirelessly controlled by a monitor the size of a cell phone and is waterproof, durable, and lightweight. This brand of insulin pump implies that customers with chronic diseases are looking for long-term solutions that require very little monitoring. Rather than having to give themselves injections, they can pre-program the pump and not have to think about it for the rest of the day. In addition, this device gives the wearer control over where it is on their body so that their specific needs are taken care of. However, the ultimate goal of the product is that it can be placed anywhere and remain unnoticed by an outsider.[26]

A wearable defibrillator was approved for use in 2002 that recognizes the need for patient mobility and independence. The LifeVest, developed by Zoll Lifecor, sacrifices the wearer's privacy for the ability to leave the hospital and regain a normal life with the assurance of continuing care. The LifeVest is a non-invasive product that is worn at all times by people with a history of or predisposition to sudden cardiac arrest. The vest has electrodes that sense the user's heart beat and will signal if an abnormal rhythm is detected. It then issues a warning signal and administers a treatment shock to restore the normal rhythm. The device is bulky, but is the first of its kind on the market, showing that the proper function of the product is always the most important aspect.[27]

Products with integrated sensors seem to be the largest segment of the market in wearable medical devices. They represent a technology that is being adapted to wearables that suit the needs of the end users. The most common use of sensors is for athletes who wish to monitor their heart rate, metabolism, and stride. Both NuMetrex and Adidas' miCoach are examples of small devices built into athletic clothing that send collected data to a compatible watch, Ipod, or computer. In fact, NuMetrex uses special fabrics which have electronic sensing technology integrated in them. The hardware then consists of the memory and transmitter necessary to interpret the data.[28] While they are not strictly "medical" devices, the success of these products indicate the public's interest in understanding how their bodies perform, and their desire to be involved with healthcare and disease prevention.

3.2 Experimental Designs

While there are relatively few wearable medical devices currently on the market, there is much more research being performed and preliminary designs being developed in the field. Again, a lot of research is focusing on which signals produced by the human body can be sensed and interpreted to improve everyday life. The most intuitive vital to monitor is the heart beat, one which has been extensively studied and tested. While the sensors may not be novel technology, their implementation in wearables is a different problem to consider. In order for the sensors to be used on a daily basis without any restrictions to activity or comfort, researchers have developed contactless EMG sensors which can be embroidered into clothing. This process requires that the sensors are miniaturized or made as flexible as possible in order to be as reliable as possible. The device is secured with conductive threads and the embroidery, which is generally more substantial than regular stitching and serves a decorative purpose, is used to connect circuits and maintain separation between the electrical components.[29]

Other research is being conducted to knit, weave, and sew sensors into garments for monitoring purposes. Regular and conductive yarns can be knit or woven into clothing in order to create conductive circuits connecting the series of sensors necessary for gathering electrocardiogram and respiratory activity. In addition, print screening with a conductive silicone can turn fabric into a piezoresistor which can sense the motion of joints.[30] The importance of these experiments is in developing new methods of implementation of existing technology while exploring the full range of e-textiles available.

Some experimental designs do not focus on the use of sensors, but rather the experience of interacting with the product. The Hug Shirt is a prototype that stimulates ones emotional well-being and connection with loved ones. It allows a friend to send a "hug," which results in applied pressure, warmth, and vibration in the receiver's shirt where the physical contact was located. The information is sent from sensors via Bluetooth over any distance and is interpreted by special software on a cell phone. Similarly, psychohaptics are touch simulations meant to treat certain mental disorders. The haptic interfaces simulate touch-therapy currently being used in hospitals. The devices include a cooling wrap, a pain inducing wristband, a vest that simulates being held, and a system for remote touch therapy. [31] Clearly, in these cases, the products are not meant to be worn continuously, but are meant to interact with the users in very specific ways. Therefore, the research being done into developing treatments for specific disorders is crucial in understanding which emotions and feelings the devices should evoke.

Lastly, the Beagle Scarf being developed by Leo Chao at the Emily Charr Institute, as shown in Figure 10, is an experimental design meant to aid autistic children in dealing with stressful situations. It is a garment that can be worn like a vest or a scarf and is meant to stimulate the different senses. Small speakers in the hood and a controller on the pocket allow the child to play music to block out other stimuli. Also, there are patches of different scents along the inside of the hood, as well as textured fabrics in the pockets to provide a broader range of feelings. While the technology involved to create this garment is very simple, it displays an in depth understanding of the patient needs and how to integrate those into a wearable device which is flexible depending on the situation, comfortable, and fashionable.[32]

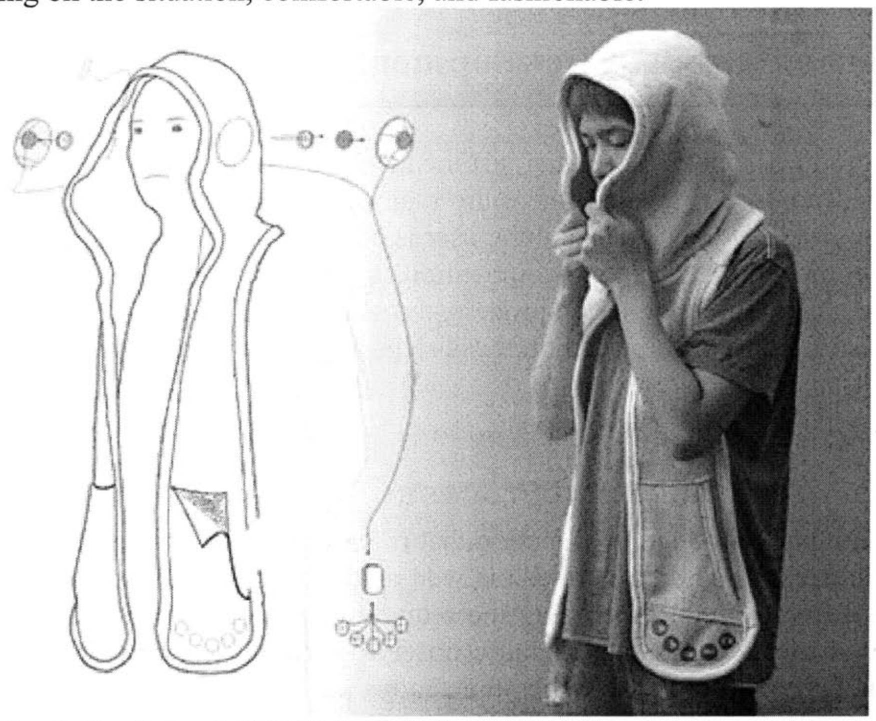


Figure 10: The Beagle Scarf--a wearable aid for autistic children incorporating sound, texture, and scent.

4 Wearable Product Development

A successful product is much more than just the manifestation of a good idea. In order to ensure a well designed product is created, there are many more issues that must be thought through. The interaction between the device and the user is among one of the most important aspects, but others include the current market, competition, aesthetics, cost, and durability. To better understand the general product design process, the steps are outlined here. For wearable devices, additional constraints are then placed on those steps and provide the engineer with a different set of requirements and challenges.

4.1 General Product Design Process

To start designing any product, the function that it is meant to perform must be well understood. The end user's needs should be defined, as well as the problem that the product is solving and the tasks it is to perform. Researching the requirements can save the designer time and help guide the initial ideas. This may include observing the user, interviewing professionals, or examining competitor's products. When the actions the product will perform are decided upon, they should be split up into independent parts, thereby creating the foundation for a modular design and product.

The next step is for the designer to brainstorm many ways to accomplish each of the required tasks. The problem can be looked at from different viewpoints, and the designer should challenge any assumptions and defer judgment. The more ideas that are generated help the creative process and can guide the decision making process. However, when the ideas are formed the mechanisms or design principles guiding the choice should also be noted. After all the brainstorming is done, a few of the most promising ideas may be chosen for a starting point.[33]

Using calculations and short experiments are the best ways to determine the feasibility of an idea. Running first order calculations of the power requirements, material properties, or size requirements can take very little time but provide a lot of information about whether the chosen mechanism can accomplish the task. Some calculations are much too complicated and time consuming to be practical, however, and in this case an experiment should be developed to gather the required information. After the analysis is done, the best idea for each module can be chosen or the designer must go back to the brainstorming phase.

Research is an important aspect of the design process after a rough idea of the product has been generated. In particular, benchmarking can help the designer to understand that status of the market, the customer's preferences, price points, and how certain technologies are being implemented. The designer should also be aware of existing patents so as to not violate copyright laws and create a salable product. More in depth analysis and support for any decisions made may also prove to be useful at this point.

At this point there is certainly enough information to start building modules of the product, if this has not already been accomplished as part of the research or experiments. While building it is likely that several new problems will present themselves making the choice of materials increasingly important. While constructing any of the modules the designer should always be looking for weak points in the design. The identified risks may be cause to look for new ideas or prompt the addition of a countermeasure. Having a backup plan in case of failure will result in a more robust and dependable product.[34]

After the initial mock-up of the product, the designer can assess how all the modules fit together, how the customer reacts to it, and the cost. Any problems will initiate another iteration of the process until a successful product is created.

4.2 Wearable Design Considerations

Development of wearable technology follows the general process as laid out above, but there are additional considerations which may be unfamiliar to some. While it is common to design for the human-product interface, there is an additional level when the product is being worn for long periods of time. Anthropomorphic data, ergonomics, comfort, range of motion, fashion, safety, ease of use, and emotional and cultural implications are examples of these factors.

When identifying the user's needs in the first step of the process, there are important new requirements that are automatically applied for wearable design. The product must always be thought of in the context of the human body, and as such must be able to conform to and move with the body—in short, it must be comfortable. Identifying comfort as a separate need allows the designer to consider the parameters which would affect the achievement of this goal. The other necessary requirement is that the product be safe, and be able to pass FDA certification.

Wearability is the sum of many different factors, and while the best effort should be made to integrate all of them, compromises will of course need to be made as a product becomes more complex. Choosing the optimum placement on the body may help to avoid obstruction of motion. In a study, researchers at Carnegie Mellon University determined that the collar, triceps, forearm, rear, side and front ribcage, waist and hips, thigh, shin, and top of the foot were areas that had the least movement and bending when the body is in motion.[35] In some cases, however, the placement is dictated by the function of the product and cannot be changed without a compromise to function.

The form of the product may also be considered to improve comfort against the skin. A concave inner profile, rounded edges, and tapered sides will act as an extension of the body and minimize snagging and personal injury. Similarly, the size of the form should be in proportion to the body, which can be difficult to achieve as body sizes vary greatly. Anthropomorphic data can aid in the selection of the size and shape of the product, or dictate the need for different products for different ranges of customers.

The method of attachment to the body is another way that product comfort can be ensured. The design should be stable, with preferably more than one point of attachment. Straps around the body can allow for adjustments so that they may fit a wider range of people, although devices built into sized clothing may also serve this purpose. The accessibility to the product must also be guaranteed—it must easily be reached, heard, felt, or seen, and the attachment cannot interfere with those functions.[36]

Wearability involves the form and function of the product, but also transcends to the cultural and emotional implications for the wearer. Aesthetics are an important aspect of the design of fashionable wearables. A good-looking, functioning product will entice the customer to use it and will help them define who they are and express that to others. Research in this area must be done, as the colors, textures, shapes, and sizes of fashion forward devices may vary across regions and years. These decisions have impacts on communication, and representation of socioeconomic status, political, and religious affiliation of individuals in society. However, how large a role they play in the finished product varies depending on the designer's goals. There are a variety of wearables in the fashion realm that vary from being high in artistic value while functionality is less important to focusing primarily on the function and limiting personal expression. If at all possible, a balance should be struck between the two in order to create a commercially viable product.[37]

As for the other crucial product requirement, safety, there are a number of precautions that should be taken. When a device is expected to be in close contact with the body there is a higher likelihood of injury. If there are any power supplies, the manufacturer's recommendations should be followed closely and the current should be kept under the pain threshold, around 0.01 Amperes.[38] Any short circuits should be prevented and the electrical devices should have some safeguarding against other metal contacts or moisture. Temperature should also be regulated so as to not cause burns or irritation. Products, ideally, are breathable and do not trap heat against the skin. Moveable parts should not have any pinch points that can cause injury. Finally, for medical devices, the functions of the product should be completely reliable, especially if the product is meant as a life-saving precaution or treatment. The FDA regulates all medical devices, and their requirements should be followed in order to ensure quality.[39]

When manufacturing the product, the cost of the product must be closely considered. Soft wearable items are usually less durable than products made of metal and plastic. Also, fashion items are usually only worn for at most a few years before they are considered outdated. With this in mind, the cost cannot be prohibitive for an item that will be worn for a short amount of time. The correct materials for the project should also be chosen, knowing that computing components are likely to far outlast the other soft materials and therefore do not need to be extremely durable themselves. However the care of any soft materials should also be planned for. If devices are integrated into clothing, methods for washing, cleaning or maintenance are needed, which may require the removal of electronics or other sensitive parts.[40]

5 Selectively Heated Therapeutic Clothing

An exploration into the design of wearable technology requires going through the entire process: from identifying a need in the market, to developing the mock-up of a product. Product design encompasses many different fields, so it is important to narrow down the scope of the problem to fields that have the opportunity for new ideas, innovation, and are best suited for soft materials. Medical devices are always in demand and there is a great opportunity to improve the lives of individuals in need.

5.1 Design Process and Choice of Materials

Without having an end user in mind, the design process began with gaining an understanding of the status of the medical device industry. Background research was done on existing wearable medical devices, as discussed in Section 3. There are many invasive devices being developed that require an extensive background in internal medicine, years of research, and FDA approval before use. On the other hand, the noninvasive devices seem to focus on diagnostics rather than treatment. Because of this disparity there is an opportunity in the field to develop wearable medical devices that are noninvasive, unobtrusive to daily life, and that treat chronic diseases therapeutically rather than chemically. As a starting point, the most common diseases facing US residents were researched. Arthritis and rheumatic diseases disable the most people, and many people are familiar with its symptoms and recommended treatments.

5.1.1 Functional Requirements

Identifying people suffering with arthritis as the client, research was then done to understand which treatments would be the most helpful to the patients. It was determined that daily heat therapy is an effective way to relieve stiffness, increase circulation, and relax muscles surrounding joints afflicted by osteoarthritis, rheumatoid arthritis, and similar diseases. At a temperature of 40°C, the heat may be applied for up to eight hours a day. The specific needs, of course, will vary from person to person, so it was deemed necessary that the ability to customize the treatment to one's own liking was present in the product.

As with all medical devices, a patient receiving treatment outside of a hospital should still have the right to privacy regarding their health. Therefore, any wearable providing treatment should not only focus on the functionality, but also be fashionable and discreet. The acceptance of new products on the market relies on using the familiar as a way to gain entry, or to overcome "Operational Inertia," as stated by Joseph Dvorak. The less the product looks like a medical device, and the less it interferes with daily activities while not in use, the more successful it will be.[41] All of the other guidelines for wearable design, as outlined in Section 4, were also taken into consideration and treated as necessary product functions.

5.1.2 Design Decisions

With the tasks in mind, different strategies for accomplishing them were brainstormed. In order to allow for patients to apply heat where they need it on any given day, the device should cover the areas most commonly afflicted by arthritis pain: the hands, wrists, elbows, spine, hips, knees, and ankles. Given that the goal of the project is to incorporate fashion with technology, only the upper or lower body could be treated while wearing typical clothing. It was decided that a long-sleeve sweater would provide the greatest opportunity to demonstrate the wearable technology and that it could be applied to other garments in the future. Wool is an insulating, non-flammable material, and was chosen for this project where safety was a concern. Unfortunately, for this application, the placement of the heating elements cannot be changed to increase comfort without a total loss of functionality. This means that the devices integrated into the sweater must take this into account and make every effort to be as thin, flexible, and unobtrusive as possible.

The most important element of the design is a moveable heat pack. Hot pads and heated blankets, socks, and jackets currently available have specific lengths of Teflon wire that resistively generate heat. However, many of these devices require power from an outlet and have cords that restrict range of use. As for ski socks, they have a 9V battery stuck to the side of the ankle which provides the needed energy. While both of these represent viable ways to power a product, they are bulky and do not focus on wearability. Instead of batteries, using solar panels to power the heat pack was discussed. Flexible solar panels have been integrated into clothing before, so it is a technology that has been proven to work in the past. The necessity of having solar panels on the outside of the clothing, however, was taken to be a disadvantage because they are recognizable and would indicate to others the presence of something unusual. In addition, if the sweater is to be used indoors, a battery would be needed to hold the charge gained by the sun, thereby largely defeating the purpose of having the panels. It was finally determined that button batteries, as shown in Figure 11, were the best choice for the project, as they have a low profile and could be easily integrated into fabric.

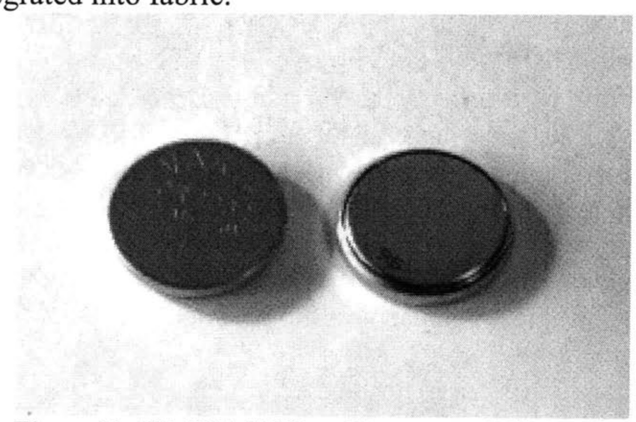


Figure 11: CR 2032 Lithium-Manganese 3V batteries.

The decision to be made was how to change the chemical energy from the batteries into thermal energy. Resistive heating is how other electric heating elements are implemented, but the choice of resistor for this application was important. Wire is conventionally used, but is an inflexible component that can be replaced with soft conductive materials. The first option was to use a knitted wool sweater and replace the sections around the joints with knitted conductive yarn, as shown in Figure 12. The conductive yarn would act like a resistor and dissipate the energy as heat in those areas. However, knitted fabric is far stretchier than woven fabric, and as noted in the Background, the yarns conduct the best when they are pulled taught. This means that in order to regulate the resistance, the material would need to be stretched over the body, which may not be comfortable for all users. In addition, the conductive element would be exposed on the outside of the sweater which would cause short circuits if it came in contact with metal objects.

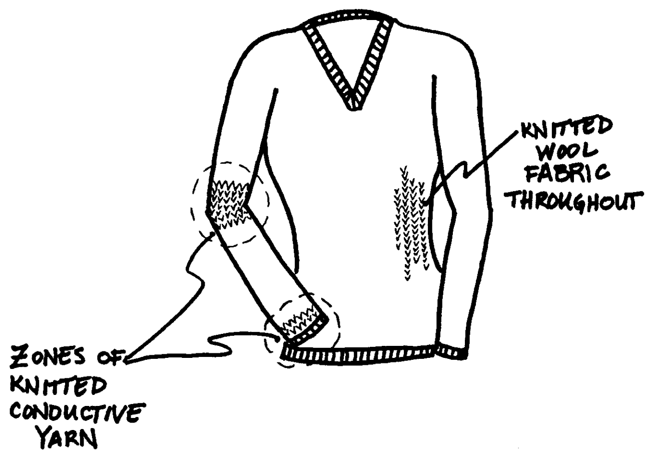


Figure 12: Sketch of a long-sleeve sweater knit with wool and conductive yarns.

The other option is using a knit or woven wool sweater as the foundation garment, and use conductive fabrics as the resistive heaters. The basic sketch is similar to the previous one, and shown in Figure 13, but indicates an important distinction. The fabric would go on the inside of the sweater, thereby creating insulation between the conductive element and other items the wearer is likely to come in contact with. This would create a double layer, but the fabric is thin and flexible, and will have the same properties as the garment. The metal fibers in the fabric are also spun with the yarns so that the fabric is soft enough to be worn on the skin. This design was chosen as the most promising because it had the most advantages and the materials were the easiest to work with. As a starting point, two of the fabrics shown in Figure 6 were chosen: a cotton and bamboo blend with silver fibers, and a cotton and polyester blend with stainless steel fibers.

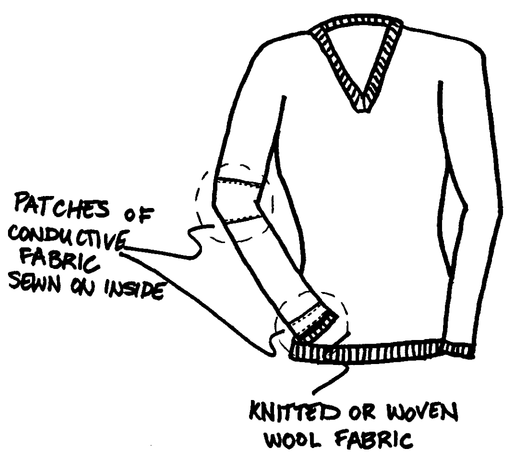


Figure 13: Sketch of a long-sleeve wool sweater with conductive fabric patches sewn on the inside.

5.1.3 Analysis

The next step in the design process was to make a simple thermal model in order to understand how much energy would be required to heat the sweater to the correct temperature. Accepted arthritis treatments include the application of high heat (up to 77°C) for 15 minutes at a time to low-level heat of 40°C for up to 8 hours. The advantage of a wearable device is that it can be worn for hours at a time without the disruption of daily activities. Therefore, this product is best suited to producing low-level heat that can be turned on when the user needs it throughout their day. The model shown in Figure 14 was created by assuming that the heat element is a flat infinite plate in contact with room temperature air and skin.

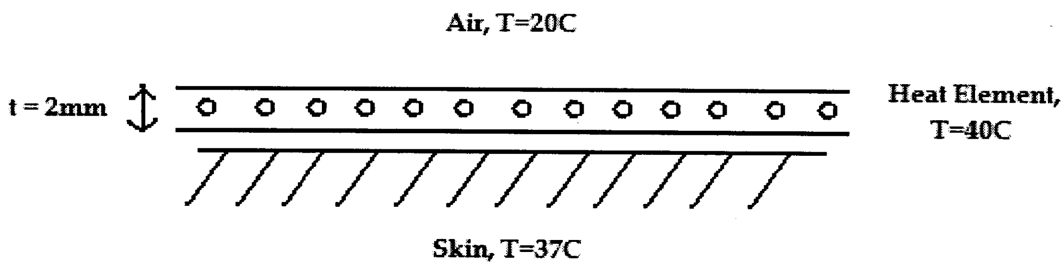


Figure 14: Thermal model of heat element in contact with air and skin.

To allow for simple calculations, it is assumed that the heat element is in direct contact with the skin and therefore the primary form of heat transfer would be conduction. However, on the other side of the plate is open air that is assumed to create forced convection. In this case the sweater fabric and boundary layer of air next to the skin are neglected as they would only add an extra layer of resistances that would make the calculation more conservative. To analyze this model, it can be viewed as a series of resistances that take into account the type of heat transfer, as shown in Figure 15.

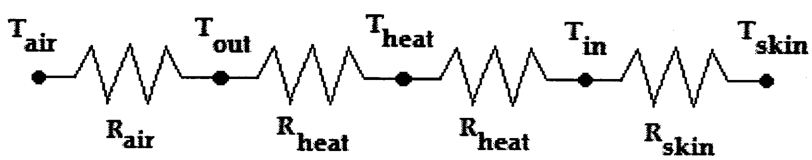


Figure 15: Thermal model as resistors in series.

The temperatures in this representation are the same as those in Figure 14, but the resistances of each material are a function of the heat transfer coefficients, type of heat transfer, and thickness. The thermal conductivity of epidermis is 0.23 W/mK,[42] the thermal conductivity of stainless steel is 16 W/mK, and the heat transfer coefficient of air is 10W/m^2K. Then, as stated in Section 2.2.1, the resistance from conduction through the heat element is:

$$R_{heat} = \frac{x}{k} = \frac{0.001m}{16\frac{W}{mK}} = 6.25 \cdot 10^{-5}\frac{m^2K}{W}. \tag{10}$$

The conduction through the skin, assuming a penetration depth of 1 cm, is similarly:

$$R_{skin} = \frac{x}{k} = \frac{0.01m}{0.23\frac{W}{mK}} = 0.0434\frac{m^2K}{W}. \quad (11)$$

Because the heat transfer through the air is forced convection, the resistance is slightly different:

$$R_{air} = \frac{1}{10\frac{W}{m^2K}} = 0.1\frac{m^2K}{W}. \quad (12)$$

Using Equation 6, the resistances can then be combined to find an overall resistance for the system:

$$R_{system} = (6.25 \cdot 10^{-5} + 0.0434 + 0.1)\frac{m^2K}{W} = 0.1435\frac{m^2K}{W}. \quad (13)$$

To find the heat flux needed from the heat element to raise the skin temperature to 40°C, Equation 9 is used with the value from Equation 13. The resulting heat flux per unit area is:

$$\frac{\dot{Q}}{A} = \frac{(40-37)K}{0.1435\frac{m^2K}{W}} = 20.9\frac{W}{m^2}. \quad (14)$$

The size of the heating element determines the total amount of heat. The size of the heating element around the elbow should take into account the circumference around the arm and the distance to cover the joint. A woman's extra large size has an arm measurement of 34 cm, and we can assume that a length of 8 cm would cover the joint. This results in an area of 0.0272 m^2 and a required heat flux of 0.568 W. The cotton and stainless steel fabric has a sheet resistance of 20 ohms/square, so for the given dimensions it has a total resistance of 85 ohms. Using Equation 3 and Ohm's Law the current and voltage for the system can be found. The relation:

$$\dot{Q} = 0.568W = I^2R = I^2 \cdot 85\Omega \quad (15)$$

results in a current of 0.082 amps. The voltage would then be 6.95 volts, or a total of 3 button batteries, to heat the joint to 40°C.

5.2 Manufacturing

The first step to creating the therapeutic garment is to choose the sweater on which everything else will be attached. As was mentioned before, wool is the safest fiber to choose for thermal applications because it is non-flammable and insulating. A thicker garment is preferable because it will help to mask any components sewn on the inside and allows the stitching to be hidden on the outside. Knit garments have more body than woven ones, and cabling is a decorative technique that actually creates a double thickness as well. For these reasons, the sweater shown in Figure 16 was chosen for this project.

Figure 16: Knit wool sweater.

Then, the batteries needed to be wired together in order to achieve the necessary voltage to heat the fabric. In order to secure the batteries, holders were needed. There were a few options for the CR2032 size as shown in Figure 17, but the best one was the beige holder on the far left because it was the narrowest and had the lowest profile. It also allows for the batteries to be easily replaced by the user.

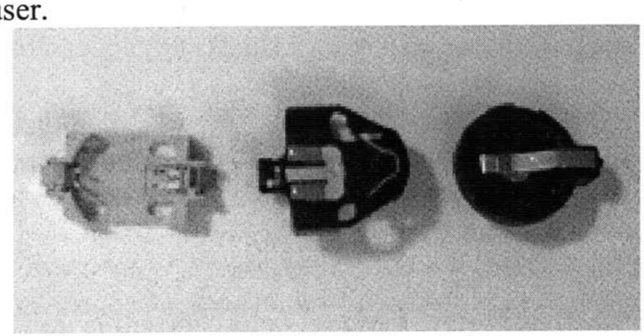


Figure 17: CR2032 battery holders.

Holes were drilled through the leads of the battery holder so that thin wires could be attached with crimps rather than with solder. Solder is a fairly brittle material so it might crack with the body's motion. Crimps allow for articulation of the wire without compromising the electrical connection. The wired battery holders were then sewn onto wool backing fabric so that the batteries are able to be moved to cover different joints, as shown in Figure 18.

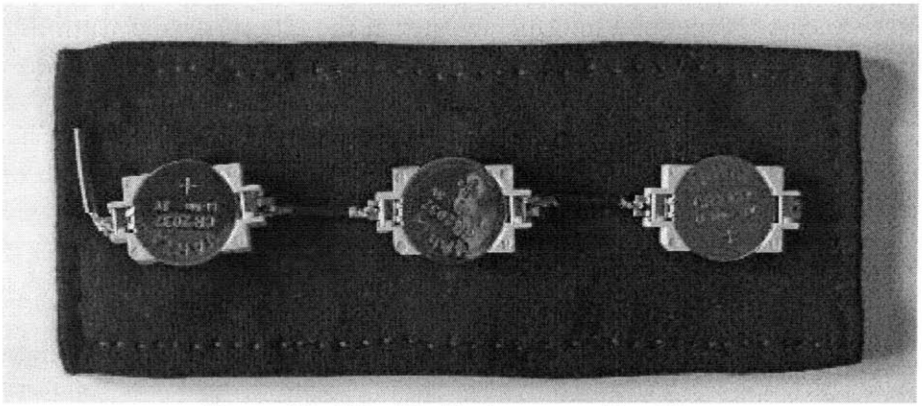


Figure 18: Wired batteries on wool backing.

Having versatility where the heated area can be moved was one of the key functions of the garment. To accomplish this, a temporary attachment method was needed. Fabric snaps are common components in clothing manufacture, and are made of metal so they can be used as electrical connections. The snaps were permanently placed in the fabric of the sweater and on the heat pack. The connections on the sweater are needed at every location that is to be heated, so it is important that they are comfortable to the wearer and look to be part of the fashion of the garment. Snaps have both a male and female section, so in order to assure comfort of the garment when the heat pack wasn't in use the female portions were affixed to the garment. The male snaps were put on the battery pack so that they could act as electrical connections as well as attachments.

The backing material on the pack acts as an insulator, so the ideal place to put the conductive fabric was on the opposite side of the batteries. When placed in the sweater, the soft conductive fabric was against the skin while the batteries faced the outside. To make the connection between the wired batteries and the fabric, the snaps were used. The fabric was cut to the correct shape and snaps to the back of the battery fabric. A short piece of wire coming from each of the two leads was crimped down by the two snap components on the conductive fabric to secure it, as shown in Figure 19. When the conductive fabric is snapped to the battery fabric, it completes the circuit and turns on the heating element.

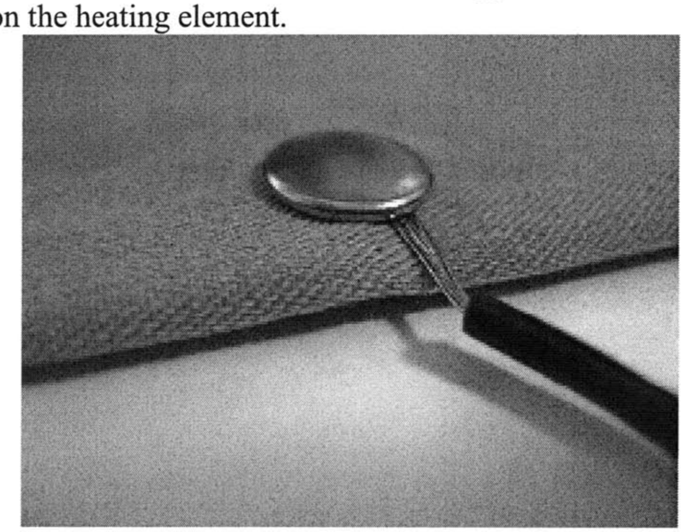


Figure 19: Electrical connection between battery wire and conductive fabric via snaps.

When the battery pack was snapped into the sweater at the elbow, as shown in Figure 20, it was barely visible when the arm was held straight. However, when the elbow was bent and the sweater fabric was stretched, the batteries were able to be seen. Having only three batteries, though, made it easy to place them just above the joint so that they wouldn't interfere with motion or the elbow resting on a table. The snaps were obvious on the outside of the garment, and while they weren't very well integrated in this sweater design, if the sweater itself was designed for this product it would be possible to turn them into design features.

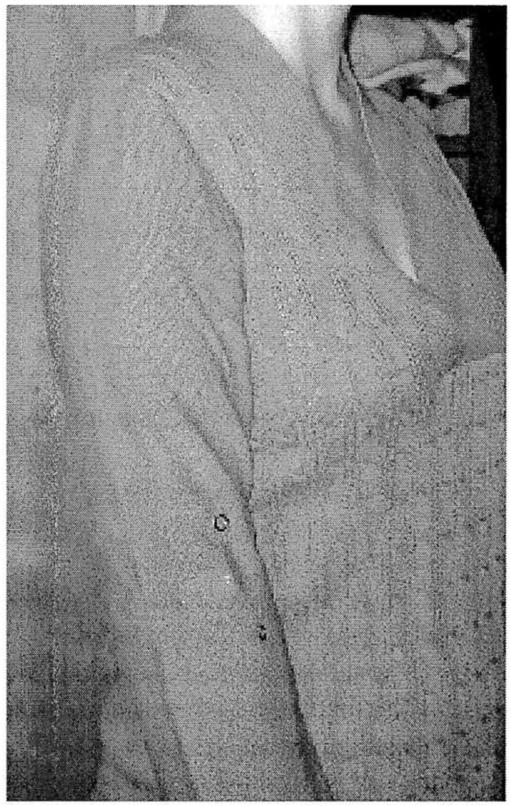


Figure 20: Therapeutic sweater with heat applied at elbow.

6 Conclusions

Arthritis is a debilitating disease that effects many people and worsens with age. While there are medications available, there are few non-invasive medical devices for the treatment of rheumatic diseases. In order to create such products, one must have a firm understanding of wearable products. Wearables must take into account the user's comfort, mobility, taste, and culture. For the Heated Therapeutic Sweater, the use of soft electronic materials created comfortable clothing. The small components were attached with fabric snaps allowing for the unobtrusive additions of technology. To determine how to heat the patient's joints to 40°C, conduction and convection equations were used, resulting in the requirement of nine volts to heat the conducting fabric. The completed garment was successful in many areas while highlighting problems in others.

At the elbow the weight wasn't a prominent issue, but at the wrist the weight created more of a problem. There was a clear discrepancy between the way each arm felt which led to self-conscience and awkward motions. This could be a problem for patients who don't experience bilateral joint pain.

When the battery pack was snapped into place, it took around 5 minutes to start to heat the entire fabric because of the conduction across the surface. Also, in the sweater, the patch feels much warmer than it did outside because the sweater fabric and air next to the body helps to trap the heat. However, with the current that the batteries were designed to product, the expected battery life is only 3 hours, which is short of the desired goal of up to 8 hours.

The total retail cost of the materials in this sweater is about $14.50. The most expensive components were the batteries at $5.13, and would continue to be a cost consideration as the batteries need to be replaced. The conductive fabric is expensive compared to normal cotton blends, and was a difficult material to find. However, it is only used in small amounts so therefore is not cost prohibitive. Given that these are retail prices and not wholesale, this is a reasonable estimation of the extra expense the consumer would expect to pay. The additional cost is very low, especially if it improves the user's life, and could easily be paid for a garment that will only last for a few seasons.

6.1 Future Work

This product could be improved in a number of ways in future iterations of the design. Firstly, the use of plastic battery holders was not ideal for this project. Instead, soft materials should have been used in order to hold the batteries so that they would be softer and create a more unobtrusive profile. Battery holders made from wool felt and conductive fabric have been created, but we were unaware of this technique when building the sweater.[43]

Also, in order to create more even heating throughout the conductive fabric, a thin sheet of aluminum could be placed on each side under the snaps to more quickly distribute the current. In addition, ideally the batteries would be rechargeable so that the user would not have costs to maintain the product. The batteries are easily removed from the holders, and could be recharged nightly to be ready for use in the morning.

Conductive thread could also be used instead of wire to create a completely soft circuit. Conductive yarns and threads are difficult to find for retail consumption however, and would be easier to use in wholesale manufacturing. The conductive fabric was also difficult to come across, but given more options, a fabric with a higher metal percentage and higher resistance would be the best for generating thermal heat.

Finally, given more time it would be beneficial to design the sweater in its entirety rather than purchasing one and altering it. This would allow the designer extra flexibility to create a more fashionable product that still accomplishes all the required functions. In particular, this would mean thinking about how the snaps are integrated into the clothing in the overall design, and using textures to hide the batteries.

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