Global Health: Prevention of Diabetic Foot Ulceration and Amputation

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Abstract

Diabetes is a growing problem in India that can often lead to the formation of ulcers and even amputation of the feet. At-home monitoring of the temperature of the feet has been shown to effectively decrease the risk of ulceration for patients who consistently comply with the care regime specified by their health care provider. There are several devices in the United States designed for at-home monitoring of foot temperature through the use of special socks or shoes, but these devices are not as applicable to patients in India who often do not wear socks or close toed shoes. In order to create a solution to affordable at-home care for diabetic patients in India, a liquid crystal thermochromic imaging surface will be created and combined with a machine learning algorithm for analysis of the temperature data. Patients can step on the surface to generate a thermal image of their feet. The colors on the thermal map will correspond to different temperatures, and these thermal maps can be photographed using a smartphone and uploaded to an app-based software to a machine learning algorithm for image processing. The software will output whether or not a patient is at risk of developing an ulcer based on any differences in temperature between symmetric parts of the feet. Providing a simple and affordable device to measure the temperature in the feet can allow patients to take control of their own health and make lifestyle changes when necessary.

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Introduction

Motivation

Diabetes has recently become a prevalent problem in India. In the United States, 13.3% of the population has diabetes while India only 8.9% . However, due to its large population, this is still 77 million people compared to 30 million in the United States [1]. This increase is in part due to the number of people that lack access to healthcare. In fact, 50-90% of diabetic patients in rural areas are undiagnosed [2]. If left untreated, diabetes can lead to ulcers that worsen to a point where it is too late to save the foot when people are able to receive medical treatment. The team's role is to create a device that can predict ulcers effectively. The team is also planning to make a low cost solution that patients could easily use at home.

Existing Devices and Current Methods

Currently, there is a brand called siren that produces socks that are worn daily and monitors the temperature of the patient's foot. These socks have sensors that constantly measure temperatures of key points on the foot and send the information to the siren app. The doctor then can notify the patient when there is any sign of inflammation or something concerning. The socks then are replaced every six months to avoid misleading data from wear and tear [3].

The team that worked on this project in the previous semester created a foldable imaging box with a temperature sensor and an infrared camera. When a patient stepped onto the box, it would then read the temperatures of the sole of the foot and send that data over WiFi to a database. The data was then easily interpreted by doctors and patients if an ulcer was present and its severity [4].

In addition to these temperature reading devices, there are devices that help patients deal with diabetes. For example, diabetic shoes offer generous space for the patient's feet. These shoes are made of protective, nonbinding, and stretchable material and have enough depth to ensure a loose fit that eases pressure points. Insoles can also be added that provide arch support and absorb shock. Diabetic socks are also worn to comfort the patient. These socks are also non constricting, soft, and moisture wicking to keep the feet cool and dry[5].

Problem Statement

Diabetic patients often lose feeling in their extremities and cannot feel an ulcer which can then lead to amputation. To fight this lack of sensation, temperature monitoring is used to predict and prevent ulcers, however this is difficult in India. Many people in India don't have access to medical treatment and often don't wear socks and shoes which are the common products for diabetics. The goal of this product is to create an easy and affordable way for patients to monitor the state of their feet. The patients should be able to take the device home and effortlessly find out if they have an ulcer developing.

Background

Relevant Biology and Physiology

Type II diabetes affects the body's ability to use insulin to regulate glucose levels. This can either be due to the body not producing sufficient amounts of insulin or resisting the efforts of insulin to maintain a healthy blood sugar level [6]. Since diabetes affects the regulation of glucose in the blood, diabetic patients develop hyperglycemia, or high blood sugar [7]. Normally, sugar obtained from food is sent into the blood through the circulatory system. In response to the spike in blood sugar that follows eating, beta cells in the pancreas secrete insulin, a hormone that elicits the fat cells in the body to absorb the glucose and subsequently lower blood sugar levels [8]. This is a regulatory process that takes place whenever blood sugar levels increase, but when diabetes affects insulin function, this natural process cannot take place, leading to hyperglycemia.

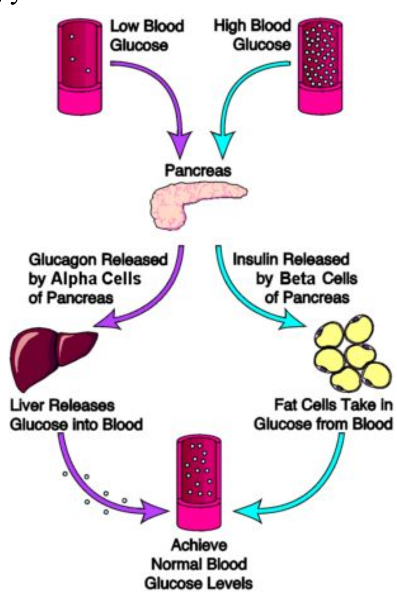


Figure 1. Insulin and glucagon regulation of blood sugar. This figure shows how insulin is released in the presence of high blood sugar to return the blood to normal glucose levels [8].

High blood sugar can damage the walls of blood vessels, particularly smaller vessels in the extremities [9]. The damage of blood vessels from hyperglycemia, combined with the harmful effects of other factors such as hypertension, obesity, and even smoking, often leads diabetic patients to develop neuropathy, a condition where sensation in the hands and feet is lost as nerve cells are destroyed [10]. When the blood vessels connected to nerve cells in the peripheral nervous system are damaged, nerve terminals are no longer adequately protected by the perineurium outer layer and can be exposed to extracellular environments that cause injury or even death of the nerve cell, leading to neuropathy (see figure 2 below) [11].

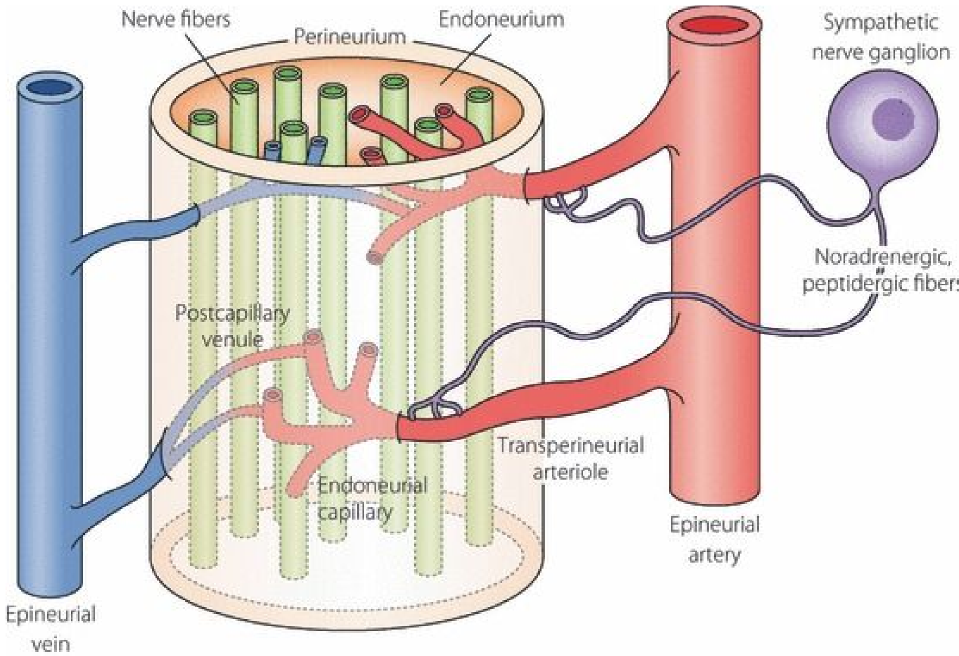


Figure 2. Diagram of nerve fiber and the blood vessels that penetrate the perineurium to supply oxygen to nerve cells. These microvessels are easily damaged, which can in turn damage the nerve endings [11].

When diabetes progresses and is not properly managed, the layers of skin on the bottom of the foot can break down to form a foot ulcer. Diabetic foot ulcers can cause the skin to turn black and leak discharge, and when severe they can expose muscles and tendons [12]. Ulcers are also prone to infection since the open wound is difficult to keep clean and free of bacteria and other substances. Infected ulcers are more difficult to treat and often lead to amputation [12]. Neuropathy can cause ulcers to worsen. Lack of sensation prevents diabetic patients from feeling pain in their feet, often leading them to put more pressure on their damaged feet than they would if they had sensation [13]. Minimal wounds can easily turn into ulcers if a patient uses their feet too much, and an improper adherence to treatment strategies often results in amputation. For all diabetic patients, the lifetime risk of developing ulceration is 25%, the majority of which will lead to amputation within four years of the initial diagnosis. [13]

Several diabetic patients will begin to suffer severe pain despite the absence of any high stress impact after traversing long distances on rough ground. Travelling long distances, a consequence of restrained access to proper footwear amplified by improper modes of transportation, is endured most heavily by rural or marginalized stratas in India who are often geographically dislocated because of economic, environmental, or migrational push or pull factors. [14] Severe pain while walking is due to two distinct types of receptors, specifically nerve endings found in the skin, that are involved in the heightened pain that diabetic patients are subjected to throughout the course of the disease. The receptors found in healthy tissue that respond to relatively high levels of mechanical stress are referred to as High Threshold Mechano-Receptors (HTMs), or receptors that respond to high pressure impinging upon otherwise undamaged skin [15].

Conversely, in the situation that the patient has already damaged the foot, Poly-Modal Nociceptors (PMNs) begin responding to relatively low pressure stimuli due to chemical products of inflammation.[15] This means that the patient experiences extreme pain due to PMNs in response to very minimal stimulation. A diabetic with a high risk for ulceration begins to feel severe pain despite the absence of high stress impacts, activating the response from PMNs caused by the pain from constant low stress. Tenderness from a consistent hard beating results in much greater pain from a much lower threshold of pressure, and after a certain duration of normal tissue responses to HTMs that report injury, inflammation induces the response of PMNs. [15]

The imminent danger that the aforementioned receptors pose to diabetic patients in India is that the foot that is neuropathic or responsive to PMNs often bears more weight than the foot that is uninjured and contains healthy tissue that responds to HTMs, further increasing the patient's risk of ulceration. This creates an indubitable need for a low cost and simplistic way to extrapolate a patient's risk of ulceration with careful and consistent at home monitoring.

Development and Process Flow

Diabetic foot screening usually involves frequent measurement of infrared skin temperature, but with small, cheap and easy to use devices. This includes electrical devices such as diodes or programmable electronic devices, and mechanical versions of temperature monitoring generally include glass thermometers with liquid. [16] Diabetic foot screening is also often achieved through devices utilizing thermal radiation that employ infrared radiation or thermography. The use of color indicators such as pencils or paints, ultrasonic sensors, or thermochromic liquid crystals and powders are also beneficial for producing heat maps of the patient's feet, as the aforementioned methods provide a cost effective and accessible solution to at home monitoring of skin surface temperatures. [17]

Furthermore, infrared thermography (IRT) by way of infrared cameras allows for effective determination of skin surface temperature, asserting the importance of infrared cameras and thermochromic materials in risk prediction of ulceration. Thermographic maps produced by IRT detect variations in plantar temperature, however, the plantar temperature distribution does not follow a particular pattern in diabetic patients, thereby making it difficult to measure the changes. Thus, an interest arises in ameliorating the analysis and classification methods used in image analysis algorithms involved in artificial intelligence and machine learning that operate with complex data structures.[18]

Producing accurate thermal images of diabetic patients' feet for analysis by machine learning algorithms involves active participation by the patient. [19] In the field of image analysis and pattern recognition, an image processing algorithm is able to produce a prediction of the classification of new images based on a prior data set with known parameters. The first of two main methods of machine learning is an algorithm for creating a data point or "feature vector" given an image. A feature vector consists of several numbers that are measured or calculated from the image. [20] These features are then used by the second part of the system, a machine learning algorithm, to classify unknown feature vectors given a large database of feature vectors whose classifications are known. [20] These images are then uploaded to an app-based software, written by code that is developed, tested, and frequently debugged, that outputs to the patient their risk for ulceration. The incentive for using an app based software in junction with machine image analysis Developing an image analysis algorithm to be more accurate in its machine learning recognition of hot spots for potential ulcers greatly increases the chance of preventing amputation.

About the Client

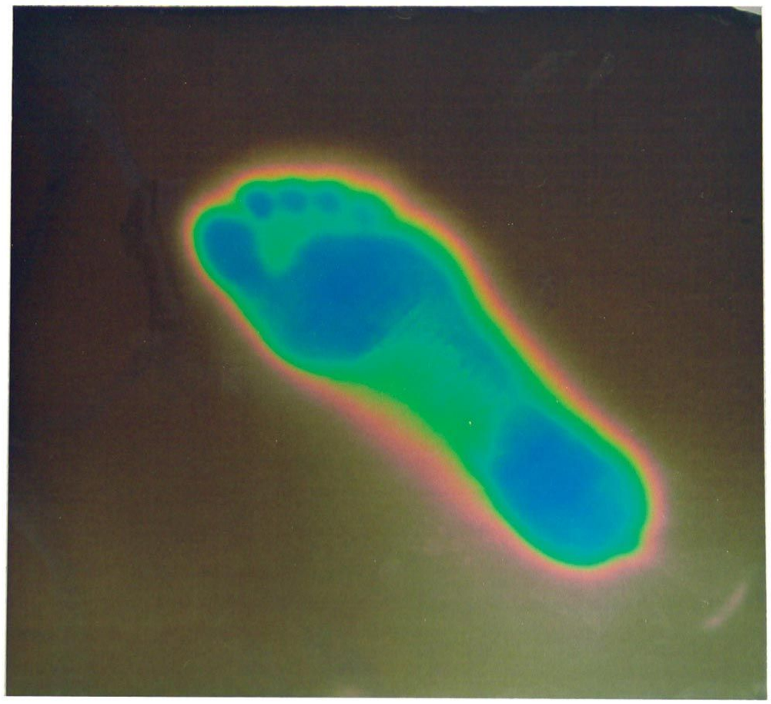
Kayla Huemer graduated from the University of Wisconsin - Madison in biomedical engineering. She is currently attending graduate school at the University of Stanford to study the intersection of healthcare data, AI, and global health. Kayla became involved with this project when she was a sophomore at the University of Wisconsin - Madison. She traveled to India in order to research the diabetes breakout that was occuring. While she was there she was offered the opportunity to collect data of patients at a hospital in India. She didn't have the funds in order to continue her research so she came back in 2018 and 2019. She was awarded the US Fulbright Fellowship in order to continue her medical device research in India. After working a year on pressure sensing footwear she started to realize that the footwear wasn't the best way to detect foot ulcers in diabetic patients. She shifted her focus and started using thermal imaging of patients feet to help detect early signs of foot ulceration. Now she is trying to integrate a more cost effective way and machine learning in order to improve the detection capabilities.

Design Specifications

To summarize the product design specification the device must be a low cost at home temperature monitoring device that is easily usinable by any patient. It also must be usable by patients that both use and don't use socks and sandals. It also must incorporate a thermochromic material injunction with an app based software and a machine learning algorithm to intake heat map images of the thermochromic material. This app will then output the risk factor of a patient's likelihood of developing a foot ulcer. One thing to note is that the machine learning algorithm must be accurate enough to recognize multiple thermal images whether or not a patient is in fact at risk of an ulceration. Also the product needs to be able to withstand multiple uses while still producing an accurate image and thermal map of the patient's feet for uploading to the app based software. See Appendix A for the full product design specifications.

Preliminary Designs

Design 1 - Insulated Thermochromic Color Changing Sheets



LC-2530 25-30°C Transition

Figure 3: *The temperature profile of a foot as represented by an insulated thermochromic liquid crystal sheet* [21].

The first design proposed by the team was chosen in order to minimize cost and maximize the ease of fabrication. Insulated thermochromic color changing sheets contain thermochromic liquid crystals (TLCs) which are molecules that can exist in a liquid state with some crystal-like order. TLCs change color due to variations in intermolecular forces at different temperatures and different molecules experience these variations within different temperature ranges [22]. Insulated thermochromic sheets usually display color changes over a 5℃ range with a tolerance of ±1.5℃ and can be customized to include protection from water and UV light. If the sheets are properly stored at room temperature with minimal UV exposure they can be reused and maintain the expected accuracy for over one year [23]. Despite the advantages of this design, complications arise from the small effective temperature ranges and mediocre accuracy of insulated thermochromic sheets. Due to the large variation in possible foot temperatures, consumers would need to buy multiple sheets, each effective over different temperature ranges, to guarantee a proper temperature profile can be collected and analyzed. This could also require the machine learning software to be trained to recognize areas of high ulcer risk for each sheet, which would prove challenging and require a large amount of data to be gathered.

Design 2 - Mix of Thermochromic Color Changing Powders

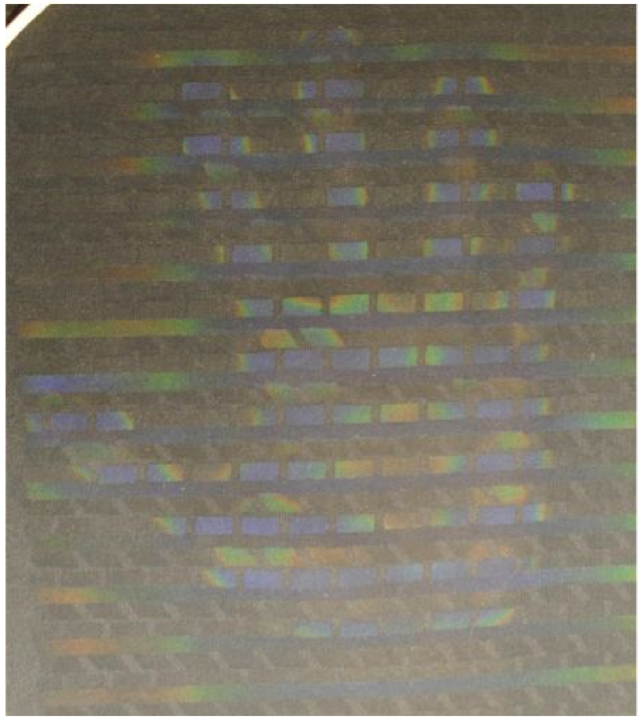


Figure 4: *The temperature profile of a hand as shown by three TLC powders each layered in a unique pattern* [24].

TLC powders can be applied to materials to create thermochromic color changing sheets. Combining powders that experience color changes at contiguous temperature ranges on one sheet would allow for consumers to purchase a single sheet that would be sensitive to a wider range of temperatures. Top coats would be used to increase the durability, and therefore reusability, of the final product. It has been shown that layering the TLC powders in unique patterns allows for significantly accurate temperature profiles to be obtained [Figure 4]. While the fabrication process of this design would be very involved, the increase in effective temperature range in comparison to the first design increases accuracy and keeps the cost low. Both designs one and two require the consumer to stand on a TLC surface, take a picture of the resulting temperature profile of their feet, and upload the image to an app with the machine learning software trained to recognize areas of high ulcer risk. The team will need to assess whether the time required to step off the sheet and capture an image will cause a significant loss in accuracy of the accuracy of the temperature profile or not.

Design 3 - IR Thermal Camera Smartphone Attachment

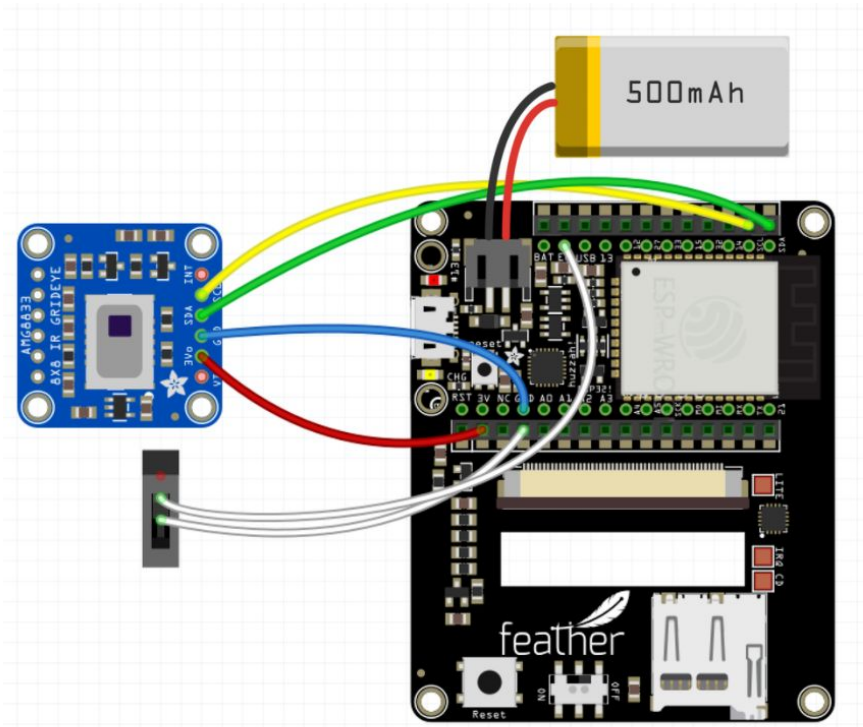


Figure 5: *Circuit with thermal camera component and display using TFT Feather* [25].

The third design the team proposed was an infrared thermal camera that could attach to a smartphone. This design would allow for digital thermal images to be taken and directly uploaded to the software based app for processing and classification by the machine learning algorithm. Such thermal cameras have the potential to be much more accurate than the other two designs. Although the accuracy of the temperature profiles is an important factor to consider, the comparatively large cost of thermal cameras to the TLC based designs outweighs the benefits of increased accuracy. It would also be difficult for a consumer to take a direct picture of the soles of their feet without assistance which would likely cause a decrease in the compliance of consumers.

Preliminary Design Evaluation

Design Matrix

Table 1. Design Matrix. Evaluation of feasible design ideas amongst different criteria. Highlighted areas indicate the highest score per category. Scores out of 10.

*Displayed as: score out of ten | weighted score

			Design 1: Insulated color changing sheets		**Design 2: Mix of color changing powders**		**Design 3: Thermal camera smartphone attachment**	
Rank	Criteria	Weight	Score (10 max)	Weighted Score	Score (10 max)	Weighted Score	Score (10 max)	Weighted Score
1	Cost	20	10	20	10	20	4	8
2	Accessibility/ Compliance	20	10	20	10	20	5	10
3	Ease of Use (for patient)	20	10	20	10	20	5	10
4	Accuracy/ Sensitivity	15	3	4.5	9	13.5	10	15
5	Durability	10	8	8	10	10	10	10
6	Ease of Fabrication	10	7	7	6	6	2	2
7	Safety	5	10	5	10	5	10	5
	Sum	**100**	**Sum**	84.5	**Sum**	94.5	**Sum**	60

Summary of Design Matrix

Our design matrix included 7 different points of criteria. These points of criteria in order of importance included cost, accessibility/compliance, ease of use, accuracy/sensitivity, durability, ease of fabrication, and safety. First, cost is one of the most important factors for our project because our main goal is to create a solution that is affordable to the average diabetic patient in India. This needs to be an affordable device that patients can purchase either directly from their healthcare provider or from an online source.

Next, compliance is a big issue for at-home medical care. Other products like temperature measuring socks would not be viable in India because the majority of people do not wear socks. Finding a solution that patients would be able and willing to comply with is important. This means the device cannot interfere with daily life, and must have a minimal amount of steps to use. Ease of use goes hand in hand with compliance. If the device is easier to use for the patient, then compliance is less of an issue. The device should be easy to use on a daily to weekly basis, and should not take up too much time. This is an important factor because if the device is not easy to use, it is not an adequate at-home solution.

Next, accuracy, it is necessary for the device to be accurate in order to properly diagnose individuals who are at risk of developing foot ulcers. The most important aspect of this criterion is not necessarily the accuracy of the temperature measurement, but of the differences in temperature of the foot. If temperature differences cannot be accurately measured, the machine learning software will not be able to accurately identify at-risk individuals. Durability is important because the device must be durable enough to take daily or weekly measurements for an extended period of time. This criterion is ranked lower than most as the materials we are working with are reliable for over one year. Ease of fabrication is one of the least important factors because we only need to know if we have access to the materials and equipment required to accomplish the project. It does not matter if the product is easy to manufacture if it cannot accurately indicate the level of ulcer risk or if the patient does not comply. Safety is the least important factor because there aren't any known health concerns associated with the materials being used.

Using this criteria we ranked each of the designs. Design 1: Insulated color changing sheets and Design 2: Mix of color changing powders received maximum points for cost, accessibility and ease of use. We gave these two designs these scores because they are cheap compared to current options, and they are both easy to use and something the patient would comply with. Design 3: Thermal camera smartphone attachment on the other hand scored much lower in these three categories because it is less cost effective and would be more complicated for the patient to use. After researching our three designs we came to the conclusion that designs 2 and 3 would be much more accurate than design 1 which is why design 1 scored much lower than the other two in this category. All three designs scored high in the durability category. Designs 2 and 3 received a full score for this category and design 1 scored slightly lower. Designs 1 and 2 are about the same when it comes to ease of fabrication which is why they received the same score; however, design 3 would be much more difficult to fabricate which is why it scored so low. Lastly, each design received a full score in the safety category because there are no known health concerns associated with the materials that we would use of any design.

After we completed the design matrix there was a clear winner. Design 2: Mix of color changing powders scored the most points and was chosen as our proposed final design.

Proposed Final Design

The proposed final design consists of a thermochromic imaging surface which will work in conjunction with a machine learning algorithm to analyze the data. The imaging surface will contain a layer of thermochromic powders mixed with a liquid or acrylic base so that it can be painted or spread over the solid surface. The thermochromic layer will be secured with a top coat that will prevent the lower layer from exposure to water or dirt so that it maintains its color changing properties. Preliminary testing will help the team determine the best solid material to apply the thermochromic powder mixture to (e.g. wood, plastic, fabric secured over wood, etc.). When fully assembled, the imaging device will have dimensions of 14 in. by 14 in. and will be a solid surface that the patient can stand on with their bare feet to generate a thermal map (Fig X below). The thermal image generated from the temperature sensitive color changing powder layer will last several minutes before fading, ensuring that the patient can take a picture of the imaging surface with their smartphone to upload to the app-based software.

Once the image is fed to the software, the machine learning algorithm will process it and analyze the colored regions. Each color will be associated with a certain temperature range, so the software will identify the different temperatures in different regions of both feet. It will assess whether or not there is a temperature difference of four degrees fahrenheit or greater in symmetric parts of the feet (e.g. the difference in temperature between the right and left heel). If there are any temperature differences that meet or exceed this threshold, the software will output an 'at-risk' result, indicating that the patient is at risk of developing an ulcer. An 'at-risk' output would mean that the patient should reduce the number of steps they take daily and the amount of time they spend on their feet.

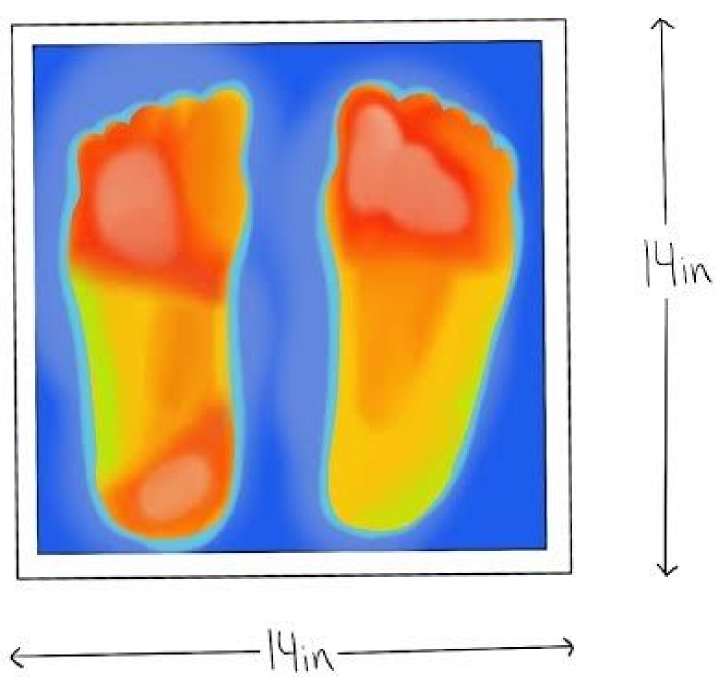


Figure 6. Top view of solid surface with thermochromic material showing a thermal image of two feet.

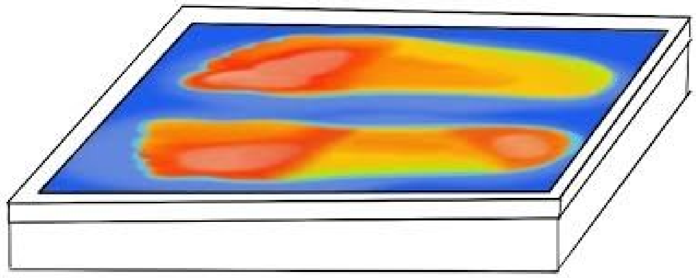


Figure 7. Side View of solid surface with thermochromic material showing a thermal image of two feet.

Development of Machine Learning Algorithm

Materials and Tools

A machine learning algorithm will be created in order to analyze the thermal maps generated when a patient takes a picture with their smartphone camera of the thermochromic material after stepping on it. This algorithm will be a type of artificial intelligence program that will be trained to classify images. In order to create this algorithm, open source code will be used to train a model using Python, a coding language. The model will require a collection of data, which will consist of approximately 200 thermal images of diabetic patients' feet taken by the client, Kayla Huemer, in India. These images will serve as the data that the machine learning model will be trained to recognize and classify. A model such as ImageAI [26] or TensorFlow 2.0 [27] will be used and imported into Supervisely, a collaborative workspace to compile and edit data and open source software [28].

Methods

In order to create the machine learning algorithm, an open source machine learning model will be used, such as ImageAI. These open source models are written in Python, and are built to import an RGB (color) image file, then classify the image type so that it can be processed. Images can either be interpreted one by one or as a dataset. For large amounts of images, like the set of thermal images provided by the client, a dataset is the best method for organizing the data. An iterator in the Python code will allow the program to run through each photo. Processing the images will involve creating a set of parameters to classify the images [27]. The team will determine a temperature scale and assign temperatures to color values. Based on these temperatures associated with colors, the code will be modified to assign temperatures to different areas of the foot. If the algorithm recognizes that there is a temperature difference of four degrees Fahrenheit or more between any symmetric parts of the foot, it will classify the image as at-risk of an ulcer.

Final Prototype

The final prototype will be a functioning code that will take an input thermal image, process it by analyzing the color of each pixel and assigning a temperature value, then outputting whether or not the patient is at risk of ulceration. ‘At risk’ will be defined as containing at least one area of the foot with a temperature difference of at least four degrees fahrenheit compared to the analogous section of the other foot.

Testing

In order to test the accuracy of the machine learning algorithm, more thermal images that the team takes will be input into the software. The output will be compared to actual data collected with a thermometer to test how often or not it correctly classifies the image as at-risk or not. Inputting these images will help to further teach the algorithm to properly identify the images it is fed.

Fabrication of Thermochromic Imaging Surface

Materials

Thermochromic liquid crystal color changing powders will be used and combined to form a mixture that will change color depending on the temperature at contact with the foot. Warmer colors will indicate warmer temperatures, with red being the hottest, and cooler colors will indicate cooler temperatures. These powders can either be purchased pre-made from a vendor in a powder or liquid form [29] or they can be assembled from a combination of cholesteryl oleyl carbonate, cholesteryl pelargonate, and cholesteryl benzoate [30]. Although they are nontoxic, appropriate eye and skin protection should be used when handling these chemicals. Different combinations of these chemicals can produce mixtures that change color at varying temperatures [30].

Table 2. Temperature range of different combinations of cholesteryl oleyl carbonate, cholesteryl pelargonate, and cholesteryl benzoate from UW MRSEC Education Group [30].

	Cholesteryl oleyl carbonate	Cholesteryl pelargonate	Cholesteryl benzoate	Transition range, degrees C
Different compositions change color over different temperature ranges.	0.65g	0.25g	0.10g	17-23
	0.70g	0.10g	0.20g	20-25
	0.45g	0.45g	0.10g	26.5-30.5
	0.43g	0.47g	0.10g	29-32
	0.44g	0.46g	0.10g	30-33
	0.42g	0.48g	0.10g	31-34

Methods

To prepare the cholesteryl chemicals into a color changing liquid with the appropriate temperature range, the cholesteryl oleyl carbonate, cholesteryl pelargonate, and cholesteryl benzoate (in the appropriate ratio listed above in Table X) must be combined in a container. The mixture of chemicals must then be heated and melted using a hair dryer or other heat source. As the product is heated and cooled, the liquid will change color based on the temperature. The liquid product can then be used immediately and mixed with an acrylic base, or it can be stored in a sealed container at room temperature for later use [30].

Final Prototype

The final prototype will consist of a flat solid surface with a layer of the thermochromic liquid crystal material secured with a top coat that will prevent any water or dirt from interfering with the color changing properties. This surface will be 14 in. by 14 in., which will be large enough for patients to stand on but small enough to store easily on a shelf. Preliminary testing will be performed to determine if wood, plastic, or fabric secured on a wooden board would serve as the best solid surface for the thermochromic powder layer.

Testing

In order to test the accuracy of the thermochromic imaging surface, the team will perform several trials where different people will step on the surface multiple times to generate a thermal map. The thermal map will be compared to actual temperature data of the feet taken with a thermometer. If the team is able to access a digital infrared thermal camera, the thermal maps generated by the thermochromic imaging surface will also be compared to real photographs taken using a thermal camera.

Results

The final prototype should be able to withstand the force of the average diabetic patient in India and accurately generate a color coded thermal image of their feet. The patient will be able to use their smartphone to take a picture of thermochromic imaging surface and upload it to the software which will use the machine learning algorithm to recognize whether or not there is a significant temperature difference in symmetric parts of the feet and classify if the patient is at risk of developing an ulcer. Expected testing results include temperature data taken from the feet of multiple test subjects and several trials using the imaging surface for each subject. The team will run a statistical analysis to determine if there are any statistically significant differences between the experimental temperature data and the output of the device.

Discussion

The thermochromic imaging surface and software should be accessible and easy to use for all diabetic patients in India. Each individual device should be inexpensive in order to make it as accessible as possible for patients, despite income level. The ergonomics of the device will be simple so that each patient can simply step on the imaging surface with their bare feet in order to generate a thermal map. The generated image will be vibrant and will stay on the surface long enough for the patient to use their smartphone to take a picture of it.

Although there are several products on the market that are geared towards aiding diabetic patients in self-monitoring their feet to prevent injury or ulceration, many of these products involve components that would decrease compliance for diabetic patients in India. Siren is a growing company in the United States that uses temperature sensing technology built into a pair of socks so that patients can monitor the temperature of different areas of their feet and modify their daily activities if they notice significant temperature changes. Products such as diabetic socks and shoes are not as applicable in rural communities in India, however, where the average person often may not wear socks and close-toed shoes, but rather go about their daily lives in sandals or bare feet. The team's design of a thermochromic imaging surface that patients simply need to step on briefly bridges this gap because patients will not have to interfere with their daily routine to monitor the temperature of their feet.

Once the team collects data on the imaging surface, it will be compared not only to experimental data, but it will also be compared to existing products like Siren socks to determine the efficiency of the product and where changes might be made. If the results of testing indicate that the device is accurate and effective, this will mean that the team's product will provide a much more accessible method for diabetic patients in India to monitor the state of their feet so that they can be proactive in making decisions that will benefit their health. This will create an avenue for at-home treatment that will benefit patients who have obstacles that keep them from accessing standard health care, such as money or distance.

The creation of this product will involve a mixture of chemicals, which will be ethically sourced from Sigma Aldrich, a large supplier of chemicals in the United States.

Conclusion

The thermochromic imaging surface made from liquid crystal color changing powders will be the design that the team fabricates and tests. This device will be a hard surface with a layer of thermochromic material on which patients can step to generate a thermal map of their feet. This color coded thermal map can be photographed and uploaded to the software for classification by the machine learning algorithm to output whether or not the patient is at risk of an ulcer. Preliminary tests will be performed to determine experimentally which surface is the best for the layer of thermochromic powder (e.g. wood, plastic, fabric, etc.). Further testing will be performed to determine the accuracy of the powders and whether or not the prototype requires any modifications.

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Appendix

Appendix A - PDS

Global Health: Prevention of Diabetic Foot Ulceration and Amputation
Preliminary Product Design Specifications
Date: 09/18/2020

Team Members: Cade Van Horn Team Leader
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Function:
The device will be a preventative solution to India's diabetic foot ulcer problem by developing a low-cost way to measure temperature from the feet of diabetic patients using thermochromic material and an app-based software to further interpret the images and thermal maps. A machine learning algorithm will be incorporated to analyze the data collected and determine whether or not a patient is at-risk of developing a foot ulcer.

Client Requirements:

- Obtain a thermal image or map of the patients' feet
- Upload the thermal images to a software/app
- Use a machine learning algorithm that we will train to recognize whether an image is of an at-risk patient or not

Design Requirements:

1. **Physical and Operational Characteristics**
    a. ***Performance requirements:*** *The performance demanded or likely to be demanded should be fully defined. Examples of items to be considered include: how often the device will be used; likely loading patterns; etc.*
        i. The machine learning algorithm must be accurate enough to recognize whether or not a patient is at-risk of developing an ulcer based on the thermal image of a patient's foot.
        ii. The device could be used anywhere from monthly to daily. It must be able to withstand several uses in one day and still accurately display a thermal map of the patient's feet that can be uploaded to the app.
        iii. The app/software must be able to withstand the process of uploading an image several times a day, potentially by multiple different mobile devices. It cannot crash during usage.
    b. ***Safety:*** *Understand any safety aspects, safety standards, and legislation covering the product type. This includes the need for labeling, safety warnings, etc. Consider various safety aspects relating to mechanical, chemical, electrical, thermal, etc.*
        i. The material used to collect temperature data and thermal maps must be safe for the patient. This includes thermal cameras and thermochromic material, neither of which can include any harmful side effects for the patient [1].
    c. ***Accuracy and Reliability:*** *Establish limits for precision (repeatability) and accuracy (how close to the "true" value) and the range over which this is true of the device.*
        i. The machine learning algorithm must be very accurate and reliable, therefore it must go through a long enough "learning process" before it is used clinically.
        ii. It must be accurate enough to recognize when a patient is at-risk of developing a foot ulcer.
    d. ***Life in Service****: Establish service requirements, including how short, how long, and against what criteria? (i.e. hours, days of operation, distance traveled, no.of revolutions, no. of cycles, etc.)*
        i. Liquid crystal thermochromic material can retain its properties for several months if handled properly. Soaking the material in hot water baths can cause the material to deteriorate faster, as well as exposure to UV light [2].

e. ***Operating Environment**: Establish the conditions that the device could be exposed to during operation (or at any other time, such as storage or idle time), including temperature range, pressure range, humidity, shock loading, dirt or dust, corrosion from fluids, noise levels, insects, vibration, persons who will use or handle, any unforeseen hazards, etc.*
    i. The thermochromic material will be used to obtain a thermal map of the patient's feet when the patient steps on the material. This can be used in any indoor setting with a controlled climate.

f. ***Ergonomics**: Establish restrictions on the interaction of the product with man (animal), including heights, reach, forces, acceptable operation torques, etc..*
    i. The thermochromic material must be easy to use by both the doctor and the patient. All that will be required of the patient will be to step on the material to collect the thermal map, and the person looking to analyze the thermal map should be able to easily take a picture of the generated thermal map with their phone camera and upload it to the app-based software, which will generate an output. This should be an easy process for the user.

g. ***Size**: Establish restrictions on the size of the product, including maximum size, portability, space available, access for maintenance, etc.*
    i. The thermochromic material needs to be large enough for both of the patient's feet, but small enough so that there is not too much excess material. One sheet needs to be able to accommodate people of many different foot sizes.
    ii. The size of the images must be compatible with the software/app. The app must be able to analyze images of different sizes and still generate a result.

h. ***Weight**: Establish restrictions on maximum, minimum, and/or optimum weight; weight is important when it comes to handling the product by the user, by the distributor, handling on the shop floor, during installation, etc.*
    i. Liquid crystal thermochromic material weighs about the same as a piece of printer paper. The weight of the paper will not be an issue for the user or distributor.
    ii. The thermochromic material must be able to withstand the weight of the patient and still generate and accurate thermal map of the patient's feet.

i. ***Materials**: Establish restrictions if certain materials should be used and if certain materials should NOT be used (for example ferrous materials in MRI machine).*
    i. The thermochromic material will be the only physical material used in the project. This will either be thermochromic liquid crystal sheets, or leucodyes that can be printed on another material. The liquid crystal sheets are more accurate than leucodyes [3], so it is likely that will be the only material used.

j. ***Aesthetics, Appearance, and Finish:** Color, shape, form, texture of finish should be specified where possible (get opinions from as many sources as possible).*
    i. The user interface of the app/software must be user friendly and aesthetically appealing. It needs to be accessible to everyone eventually, so text must be readable and the image uploading process should be easy.

ii. The output generated by the app should be easy to read and non-offensive if a non-desirable (at-risk) outcome is generated.

2. Production Characteristics
    a. ***Quantity**: number of units needed*
        i. Only one application needs to be created.
        ii. While testing the device, only a few sheets of thermochromic material need to be used to ensure the accuracy of the device and system.
        iii. If the product is marketed to the public, each individual using the device will require their own sheet(s) of thermochromic material.
    b. ***Target Product Cost**: manufacturing costs; costs as compared to existing or like products*
        i. There is no set budget for this project.
        ii. One 12x12in liquid crystal sheet is $25.95 [4].

3. Miscellaneous
    a. ***Standards and Specifications**: international and /or national standards, etc. (e.g., Is FDA approval required?)*
        i. There are several FDA regulations on temperature sensing devices, although most apply to electronic devices. The team's thermochromic imaging surface will not include any electronic components that will need to comply with FDA guidelines, but if the project progresses to the point of human subject testing and involvement, FDA guidelines and regulations will need to be followed [5]
    b. ***Customer**: specific information on customer likes, dislikes, preferences, and prejudices should be understood and written down.*
        i. There are no specific requests from customers since there is no one customer. The client wants the device to be applicable to all customers/patients in India.
    c. ***Patient-related concerns**: If appropriate, consider issues which may be specific to patients or research subjects, such as: Will the device need to be sterilized between uses?; Is there any storage of patient data which must be safeguarded for confidentiality?*
        i. The reusable thermochromic imaging surface will need to be easily usable by the patient.
        ii. The imaging surface must be big enough to accommodate a variety of patients' feet.
        iii. Images of the patient's thermal maps that are uploaded to the app will not include any personal data, so no personal or sensitive data will be collected or saved.
    d. ***Competition**: Are there similar items which exist (perform comprehensive literature search and patents search)?*
        i. There is a brand called siren that produces socks that are worn daily and monitors the temperature of the patient's foot. These socks have sensors that constantly measure temperatures of key points on the foot and send the information to the siren app. The doctor then can notify the patient when there is any sign of inflammation or something concerning. The socks then are replaced every six months to avoid misleading data from wear and tear [6].

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