Helmet Temperature Sensor Project

BME 401 Senior Design Progress Report

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1 Introduction

According to the Center for Disease Control and Prevention, between 1979 and 1997, there were 7,000 deaths related to excessive heat in the U.S.[1] Heatstroke is a serious concern for athletes, specifically football players, as they exercise in the heat, have a greater risk of dehydration, and wear helmets that block the ventilation of the head. Among U.S. high school athletes, heat illness is the third leading cause of death and disability. Since 2005, 39 football players have died from heatstroke, with 29 of those being high school athletes.[2] Mortality rate and organ damage from heatstroke are directly related to length of time between core temperature elevation and initiation of cooling therapy.[2] Heat illness and heatstroke are preventable if an athlete is warned and seeks appropriate treatment prior to core temperature rising above a certain temperature. In order to prevent further death or injury, a monitoring device needs to be created to detect a football player's core temperature during physical activity and alert them when their temperature is reaching dangerous levels. This monitoring system could prevent death and injury to many players every year.

1.1 Design Requirements

The ultimate goal of the proposed device is to use a thermometry system that is integrated into current football equipment so that the subject can be observed for early indications of heat illness. The design must be able to take a temperature reading, whether orally in a mouth guard or from the temporal artery along the forehead, and relate it to the core body temperature of the subject. An oral temperature sensor will need to account for the presence of saliva and other environmental factors in the mouth. Similarly, a design taking temporal temperature readings will need to account for the ambient temperature and the presence of moisture on the forehead. The system must be able to relate these temperature readings back to the core temperature of the subject. Should the temperature increase beyond a set threshold, an alarm will warn the athlete that he or she needs to seek medical attention. This threshold will be adjustable, but a general value will be set at 38°C, which has been shown to be related to the onset of heat exhaustion. Any temperature recorded at higher than 40.5°C indicates heatstroke, and the subject should be immediately taken to see a medical physician.[3]

Special considerations that must be made relate to the power lifetime of this system. The power supply needs to be able to run the device for a complete season without replacement or recharging. The National Football League (NFL) and the National Collegiate Athletic Association (NCAA) - Division I have the two longest football seasons at 26 and 23 weeks, respectively. These lengths represent weeks of team-run preseason, regular season, and postseason activities. NCAA rules do not allow athletes to practice for more than 20 hours per week. Assuming that all players are in full equipment for all 20 hours, the device would need to operate for 460-520 hours. To prevent early failures, a 15% excess should be built in so the device can run for about 600 hours.

In the end, the important design requirement is that the system is accurate enough to detect temperature to within 0.1°C.[3] The system must fit inside current football equipment. The weight of the components should not cause a noticeable difference in the equipment's weight distribution and position of the equipment on the athlete. Ideally, the system will be no more than 2-3 ounces.[20] The warning signal should be able to easily alert the subject that he or she needs to seek medical attention. This could be a sound in the range of 70-75 decibels (dB), a light visible from 100 yards away, or a vibrating component that generates at least 1.2-26.2 g (Noise, Schmidt, Hammerle). The final product should be easy to use by subjects with limited knowledge of the product and should not be invasive. More specifically, the subject should not be at risk of accidental injury from the system. Reliability and durability are important as well, since accidental alarms would be both disruptive to the game and annoying. Given the impacts the system may experience, it should still be able to operate after impacts up to 300G.[20] At this point in time, the cost of the product is not a concern since a proof of concept is more important.

2 Design Alternatives

2.1 Thermometry Locations

Several requirements affect the choice of the thermometry process for the system. First, the thermometer must be accurate within $\pm 0.1°C$, and it must be able to account for ambient air and other conditions which could otherwise skew the core temperature measurements. Additionally, the thermometer must be of the appropriate size to fit into the desired location of use.[3] Finally, safety must be considered when choosing an appropriate thermometer. Digital thermometers are much safer than glass thermometers due to the fact that they don't contain hazardous chemicals such as ethanol or mercury. Possible thermometry locations include the rectum, axilla, esophagus, skin of the forehead, ear, mouth, and temporal artery.

2.1.1 Rectal Temperature

Rectal temperatures have been accepted as the most accurate way to obtain a core temperature reading.[3] Although this would be the ideal location to take an accurate core temperature reading, obtaining a rectal temperature from a football player is impractical due to its invasive nature.

2.1.2 Axillary Temperature

Placed under the armpit, axillary thermometers are less practical than oral temperature because the thermometer takes longer to reach equilibrium. Axillary temperatures have also been found to be less accurate in comparison to oral, tympanic, and rectal temperatures.[3] Furthermore, axillary temperature measurements have been found to be lower than actual core temperature measurements, particularly in athletes. Since these measurements can be inaccurate, it would not be the ideal way to measure core temperature in football players.

2.1.3 Esophageal Temperature

This method of temperature measurement is generally used in clinical settings. Many believe this to be a reliable method of core temperature measurement because it is closely located to the left ventricle and aorta of the heart. It is an invasive method to measure the core temperature and can cause a person discomfort when the thermistor is inserted into the nasal passage.[3]. This would not be a reasonable manner to constantly monitor the core temperature of a football player because of its discomfort and invasive nature.

2.1.4 Body Surface Temperature

Body surface temperatures have been found to be less reliable than other methods when used to derive the core temperature, but they can still provide a reasonably accurate temperature reading. Readings are often taken by direct contact of thermistors, but ambient air can have a significant effect on the temperature readings taken on the skin.[3] Body surface temperature is a method of thermometry that should be considered for use in the system.

2.1.5 Tympanic Membrane Temperature

The ear canal is a location that is easily accessible to make temperature measurements. Branches of the internal carotid artery give blood to the tympanic membrane and receive blood coming from the heart, so the temperature would presumably be similar to that of the actual core temperature. However, studies done on measuring core temperature based on the tympanic membrane have suggested that it is not an accurate method, especially during physical activity. Errors can occur as a result of dirt, inaccurate placement, and lack of the skill of person taking the temperature.[3] If a tympanic membrane temperature were to be used to determine core temperature in a football player, an ear piece would likely be added to the helmet which the player would place in their ear. However, there would be no way to guarantee a temperature reading from the proper location for an accurate measurement, and the semi-invasiveness of the device's insertion into the ear canal render this a method less favorable than some of the others mentioned.

2.1.6 Oral Temperature

Oral temperature is currently the most popular method for finding a person's core body temperature. The advantages of oral temperature include the location's easy accessibility and its ability to change quickly with a change in body temperature. Oral temperature tends to be influenced by consumption of cold or hot fluids or irregular breathing patterns. Especially for athletes, rapid breathing through the mouth can prevent accurate measurements from being taken, but does not shift the temperature reading by an unreasonable amount. The preferred location for measurement is under the tongue.[3] For the purposes of a football player, oral temperature has potential because a mouth guard could be used to integrate the proper technology needed to obtain an oral temperature.

2.1.7 Temporal Artery Temperature

The temporal artery is approximately 1 mm below the skin in the forehead, coming closest to contact with the skin at the temples. This makes it very accessible and for a low risk of injury. In this particular vessel, high and stable perfusion is maintained. Many temporal artery scanners are used today in household and medical settings, with several made by Exergen Corporation. These scanners, as shown in Figure 1, use infrared technology in order to take readings of the core temperature from the temporal artery.[4] Although this method has been found to be fairly accurate when related to core body temperature, this method has yet to be fully tested or researched for use in athletes.[5] This option would be in a convenient location for the system elements to be integrated into an existing football helmet.

Figure 1: Infrared temporal artery thermometers developed by Exergen Corporation are swiped across the forehead to obtain a reading. Source: Exergen Corp.

2.1.8 Initial Analysis of Thermometry Locations

The temperature sensing device that is decided upon must be integrated into existing personal protective equipment. With this limitation in mind several of the above options can be taken out of contention including rectal temperature, esophagus temperature, and axilla temperature. The temporal artery temperature and tympanic membrane temperature systems could be integrated into a football helmet. The oral temperature method could be easily integrated into a mouth guard. Body surface temperature could be integrated into either system.

2.2 Thermometry Methods

Several different methods can be used to collect temperature data for analysis. Infrared technology can be used in order to sense the heat of the blood of the temporal artery under the skin. Historically, glass thermometers were used to measure oral temperature, but digital thermometers have become commonplace. According to the U.S. Environmental Protection Agency, broken mercury thermometers can release mercury vapors that can be very harmful.[6] Several other chemicals have been used to replace mercury thermometers, but the use of electronic thermometers is still most common. If an oral temperature measurement were to be used, it would be much safer to use an electronic thermometer rather than a glass thermometer containing a dangerous chemical substance.

There are several different types of temperature sensors that can be used to sense temperature. These options include thermocouples, thermistors, resistance temperature detection, and infrared technology. In addition to these options, different thermochromic options were considered including leuco dyes and liquid crystals.

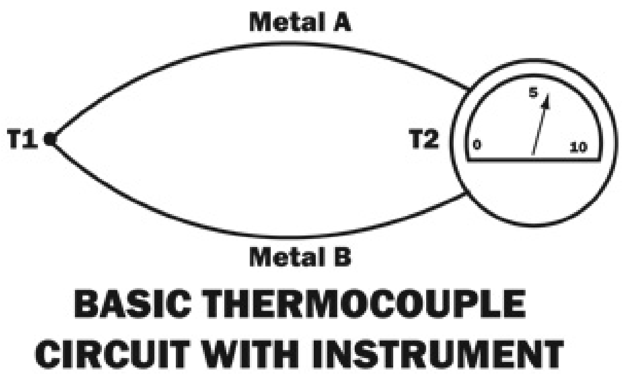
2.2.1 Thermocouples

Thermocouples (Figure 2) are temperature sensors that determine an object's temperature by direct contact. Thermocouples use two different and dissimilar metals to make a temperature reading. A voltage is created when the temperature at one junction of the metals (the reference) is different from the temperature at another junction (the temperature to be measured). The voltage created is then converted into a temperature reading. Thermocouples are inexpensive and reliable. A battery is not needed to operate a thermocouple and they can be used over a wide range of temperatures, performing well at over 2000°C.[7] After prolonged use, thermocouple readings tend to lose accuracy, especially in comparison to other methods. Thermocouples are not ideal when precision of less than 1°Cis required, as in the current situation.[8]

2.2.2 Thermistors

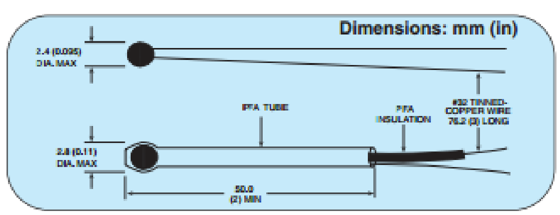
Thermistors (Figure 3)have some similar characteristics to thermocouples including that they are temperature sensors that determine an object's temperature by direct contact. Thermistors are also fairly inexpensive, have good accuracy, and are easy to use. Thermis-

Figure 2: A basic thermocouple has two junctions. One is a reference junction while the other is the sensing junction. Source: Delta T



tors are made out of semiconductor material and their resistance varies with temperature, hence their name. So, when a temperature change occurs the resistance will change by an expected amount.[7] Thermistors come as either negative or positive temperature coefficient types. Negative temperature coefficient types are used most commonly. Thermistors can be accurate to within ±0.1°C and can measure over a wide range of temperatures, depending on the thermistor resistance that is chosen.[14]

Figure 3: Typical thermistor size specifications on an Omega thermistor. The thermistors are small in size but provide good accuracy. Source: Omega Engineering



2.2.3 Resistance Temperature Detectors

Similar to thermistors, resistance temperature detectors (RTD) change resistance with a change in temperature. Pure metal is used for the material in RTDs, making them different from thermistors. In addition, they also differ in their temperature response as RTDs have a more linear change than thermistors. RTDs can be used over large temperature ranges from -50°C to 500°C.[7] Thermistors tend to have a higher change in resistance per degree change in temperature and a faster response to temperature changes when compared to RTDs.[14]

2.2.4 Infrared Sensors

Infrared sensors can be used to measure surface temperatures. When used to measure core body temperature, infrared sensors capture emitted heat from the blood supply. They have the ability to convert thermal energy into an electrical signal while using equations to take into account ambient air. Infrared sensors can measure temperatures over a range of -40°C to 125°C. Infrared sensors require a small amount of voltage to run and do not consume a lot of power.[7] Infrared technology can be used in either a temporal artery or the tympanic membrane temperature measuring options.[3]

2.2.5 Thermochromic Materials

Leuco Dyes Leuco Dyes are a type of thermochromic technology which can change color in response to change in temperature. Leuco dyes are often used in advertising and consumer packaging. Leuco dyes can change color reversibly and can be used in a large variety of inks and plastics. Leuco dyes are less precise than other forms of liquid crystals and require approximately a 3°C change in temperature to change color.[9]

Liquid Crystals Liquid crystals are another common form of thermochromic technology that is used. Liquid crystals, as explained by their name, exist in a state between liquid and crystal. Liquid crystals tend to be more expensive than leuco dyes but they are also more sensitive to temperature change. Liquid crystals can be sensitive to temperature changes as small as 0.2°C. Liquid crystals can be made to change color between -30°C and 120°C. They have the ability to be long lasting, if the liquid crystals are not exposed to UV light, high temperatures or strong solvents.[9]

2.3 Alert Methods

2.3.1 Vibration

Vibration motors, similar to those used in tactile feedback and cellular devices, would provide a means of notifying the player of the temperature rise. While the strength of vibration motors depends on the size of the motor, and is thus restricted to the space in which it is placed, such an alert method could be encased within the mouthguard without suffering a significant reduction in the potency of the alert.

2.3.2 Sound

Auditory feedback generated from a high enough temperature would not be feasible, as the environment within the mouthguard dictates that any sort of speaker be placed within the mouthguard plastic. As such, the plastic is likely to mute the sound and generate an insufficient alert for the athlete.

2.3.3 Light

A light-emitting diode (LED) is a plausible design that would turn on when the temperature rose sufficiently. The downside to such a design would be two-fold – any visual stimulus for the player would require removal of the mouthguard to be visible, and thus require additional time, and the requirement of a light exposed for the player to see creates exposure of the eletrical component to the player's mouth.

2.3.4 Wireless

Wireless transmission of temperature data gathered from the athlete's mouthguard to a side-line trainer or coach is would allow for real-time tracking of trends in a player's temperature. The design of such a system with wireless data gathering and transmission capabilities on top of the basic temperature sensing system would require a significant amount of time. Furthermore, a potential conflict of interest between sideline staff and player may occur if the player's well-being is not the priority.

2.3.5 Thermochromic Mouthguards

As previously mentioned, mouthguards whose plastic either contain or are coated with temperature-sensitive leuco dyes or liquid crystals already exist.[9] Although the temperature sensitivity of such materials, especially liquid crystals, may be sufficient for the system design requirements, the same problem exists with such materials as a light alert, in that visual stimuli require removal of the mouthguard, and as such are not as efficient as other methods in alerting the player.

2.4 Power Supply Options

The system design requires an effective energy supply to power the components. Specifically, the power supply is required to power the system throughout the entire season without having to be recharged or replaced, and the supply needs to be incorporated into existing protective equipment. Some other parts of the project that influence the type of power supply used are the type of thermometer used, the type of alert system used, and the frequency of temperature scans. These last three factors will define the energy that will need to be drawn from the power supply. The thermistors being considered for the system have a maximum voltage in between 2 and 4 V and a maximum current between 450 and 650 μA.[14] However, the usual operating level of the thermistor is actually closer to 15 μA. The alert systems under consideration that would create an auditory, visual, or tactile response require no more than 3 V and run at operating currents less than 50 mA.[15]

2.4.1 Generators

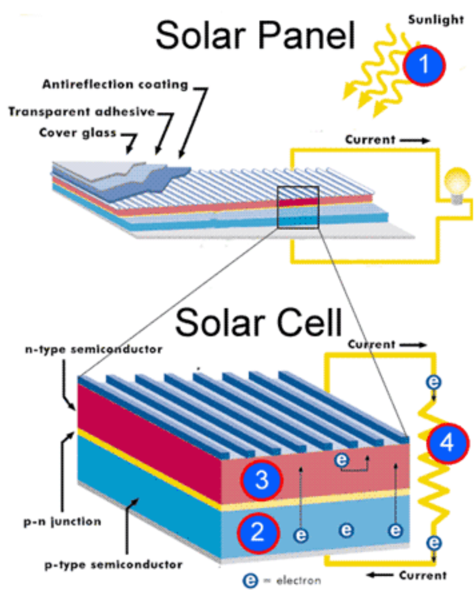
Power could be supplied to the device by any setup that would provide electricity to all components of the system. In other words, the power supply could be a generator, solar panel, piezoelectric system, or a battery. While any of these options could supply power to the system, not all of them are easily incorporated into current equipment. For example, some of the smallest commercial generators on the market like the Honda EU 1000i can provide 50 times more voltage than the system will need but is far too large and heavy to actually integrate.[16] There are homemade varieties of generators that can be made with magnets, wires, and an axle. While these options can provide the voltage necessary to power the system, they require moving parts that would need to be contained in a housing so that the athlete would not risk contact with the generator or exposed wires. This added level of complication would mean much higher risks for the design.

2.4.2 Solar Power

Solar panels have a similar problem as the generator in that they can produce electricity for the system but the panels would be unrealistic due to the size and the environment that they need to work. First, the panels would need to be in direct sun light meaning the athletes would need panels on their body or helmet, which depending on size and location, could be very awkward and obstruct the athlete's motion. The panels' placement brings up another issue. For main athletic events, especially football, there is physical contact which could damage the panels. Researcher have noted that the panels themselves are made with durable glass, but the cells inside the panel are fragile and will be more prone to break downs if the panel is thin.[17]

Piezoelectricity could be a non traditional way to deliver energy to the system. The principal of piezoelectricity is that forces that are applied to piezoelectric materials will create deformations that cause the movement of electrons in the material. This current can then be harnessed and used to run devices.[18] Piezoelectricity already has been shown to

Figure 4: Solar panels require sun light in order to generate energy, and as such, are dependent on the weather. Furthermore, any potential placement of solar cells in a location favorable for sun light would render them susceptible to damage upon impact.



be able to produce and deliver energy to small medical devices by students from Worcester Polytechnic Institution. In their proof of concept, they used a piezoelectric material that was placed in the heel of the person's shoe so that each step of the individual generates electricity. In order to use this technology for the design, considerations would have to be made on whether having the piezoelectric material in the heel will work.[19] The drawbacks are that the athlete would need wires to run from the shoe to the rest of the thermometry system. An alternative location for the piezoelectric material is in the helmet. With each step, the helmet presses against the skull and as long as the material does not compromise the protective integrity of the helmet, there would be cyclic generation of electricity with every step. A special consideration should consider that the electricity generated by using piezoelectricity and the walking cycle will not be constant unless the energy generated from the piezoelectric material is store in a battery. In the end, this power supply on its own would be a novelty product that unfortunately may not be very user friendly unless all of the piezoelectric materials and their leads can be isolated in the helmet as oppose to having connects from the shoe to other parts of the device.

The most traditional power supply for this type of device would be to use a battery cell. While batteries are well established power supplies for toys, laptop computers, and other devices, there are almost an infinite combination of sizes and types of batteries. Each type of battery has its own set of advantages and draw backs based on the chemical reactions that occur in the battery. The recommended battery can very well change from device to device and requires the understanding of the ideal use of the battery. When looking into what batteries offer the best power supply for the device, there are three things to consider: voltage and current levels of the battery, its size, and the safety of the materials in the battery. The third consideration is because the power supply will be around the human body and any leaking batteries could present a safety hazard.

Batteries are currently used to power devices in football equipment. Some quarterbacks wear helmets that are specially fitted for headsets to communicate with the sidelines. These headsets are powered by disposable batteries but have not been updated. These communicator helmets have been shown to be safe even though they are filled with more heavy batteries than they require.[20] All things considered, chemical battery cells are the power supply that is most likely to be small enough to fit into current equipment and deliver enough energy to run the thermometer and the alert system. The fact that there are small batteries like button cell batteries, whose chemical reaction is specifically formulated to power low drain devices for an extended period of time, only makes batteries a more appropriate option.[21]

3 Analysis Performed to Choose Design

The Pugh Chart was designed with multiple design considerations listed for each type of weighted variables. The design considerations include the location of the system, the method of sensing the temperature, and the different type of alert systems that can be used. Although multiple Pugh charts could have been used, these design considerations were too dependent on each other to be included in separate charts. For example, whether or not infrared technology would be accurate way to determine core body temperature is very dependent on whether or not it is used in a helmet or a mouth guard.

Table 1: Pugh chart generated for designs using the helmet.

		Location: Helmet											
		Infrared Temporal Temperature				Skin Thermistor Temperature				Infrared Tympanic Membrane Temp.			
Variables	**Weight**	Sound Alert	Vibration Alert	Light Alert	Wireless Alert	Sound Alert	Vibration Alert	Light Alert	Wireless Alert	Sound Alert	Vibration Alert	Light Alert	Wireless Alert
Client Preference	10	5	5	5	5	5	5	5	5	5	5	5	5
Time	10	7	7	8	4	7	7	8	4	7	7	8	4
Size	7	6	5	6	4	7	6	7	5	6	5	6	4
Weight	7	6	5	6	4	7	6	7	5	6	5	6	4
Cost	4	7	7	7	5	8	8	8	6	7	7	7	5
Accuracy	8	9	9	9	9	6	6	6	6	7	7	7	7
Susceptibility to damage	6	7	7	5	7	7	7	5	7	7	7	5	7
Safety	10	7	7	6	7	7	7	6	7	6	6	5	6
Alert Effectiveness	8	9	7	5	6	9	7	5	6	9	7	5	6
Total		**488**	**458**	**444**	**398**	**482**	**452**	**438**	**392**	**462**	**432**	**418**	**372**

Table 2: Pugh chart generated for designs using the mouthguard.

		Location: Mouth Guard													
		Infrared Temperature				Thermistor Temperature				Thermocouple Temperature				Leuco Dye	Liquid Crystal
Variables	**Weight**	Sound Alert	Vibration Alert	Light Alert	Wireless Alert	Sound Alert	Vibration Alert	Light Alert	Wireless Alert	Sound Alert	Vibration Alert	Light Alert	Wireless Alert		
Client Preference	10	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Time	10	7	7	8	4	7	7	8	4	7	7	8	4	8	8
Size	9	6	5	6	4	7	6	7	5	7	6	7	5	9	9
Weight	7	6	5	6	4	7	6	7	5	7	6	7	5	9	9
Cost	4	7	7	7	5	8	8	8	6	8	8	8	6	5	5
Accuracy	8	7	7	7	7	8	8	8	8	6	6	6	6	3	3
Susceptibility to damage	6	6	6	4	6	7	7	5	7	7	7	5	7	8	8
Safety	10	7	7	6	7	7	7	6	7	7	7	6	7	6	6
Alert Effectiveness	8	5	9	5	6	5	9	5	6	5	9	5	6	5	5
Total		**486**	**502**	**474**	**424**	**520**	**536**	**508**	**458**	**504**	**520**	**492**	**442**	**506**	**506**

In the core temperature monitoring device, all components of the system must be integrated into existing protective football equipment.[20] Based on this design specification, the helmet and mouth guard are the most reasonable pieces of equipment due to their proximity to current standard temperature sensing locations. These temperature measurements include readings taken along the temporal artery or in the mouth.

In the decision matrix, client preference, time, and safety were weighted the most. The client specifically requested that a mouth guard be considered because they are planning to develop other monitoring devices that could be incorporated into mouth guards.[20] While a temperature monitoring system in the helmet could be very useful, it does not align with the client's future business strategy and as such, the mouth guard design will be pursued over the helmet temperature sensor. Due to time limitations, a final design must be delivered by early December. This time limitation does not allow for extensive research into the use of wireless technology to communicate with the sidelines when a player is in danger of heat related illness. Safety is another primary concern as the components to measure the core temperature would be integrated into personal protective equipment and would be in close contact with the mucous membranes of the mouth. The integrity of the equipment cannot be altered due to the monitoring system that is put in place.

Leuco dyes and liquid crystals were other design options that were considered. Mouth guard plastics incorporating either would be able to act as both an analog temperature sensor and as an alert system. Leuco dyes lack sufficient precision, as they require up to a 3 degree Celsius temperature change in order to change color.[9] This range is too large to be a good indicator for when heat illness is setting in. Liquid crystals are more precise than leuco dyes, but they lose temperature sensing accuracy upon exposure to UV light, high temperatures, and strong solvents.[9] Given that mouth guards are worn in outdoor sports and often boiled in order to make teeth impressions, liquid crystals would not be ideal for a core temperature sensing mouth guard. In addition, current patents exist for temperature sensing mouth guards using thermochromatic inks and pigments and liquid crystals.[22]

There are several options that were explored in order to take an oral temperature. Infrared technology is currently used to detect temperatures in the temporal artery and tympanic membrane. These locations are ideal for infrared technology to be used because they have a large blood flow coming through arteries directly from the heart and they are the only locations close enough to the skin to provide accurate readings.[5] However, in the mouth there are no such arteries making infrared technology a less viable option.

The alert system is a central part of the device and must be able to quickly notify a player when they are at risk for heat related illness. An alert system that uses sound to warn the player of danger would not work with the system in side of the player's mouth. The noise would difficult to hear if the speaker was enclosed in the mouth guard. Football games and practices are often very loud and noisy so,having a sound alert could make it difficult for a player to identify the noise coming from their mouth guard. An alert system that uses light to warn the player of danger would create exposed parts if the light was to be visible to the players or his teammates. This would lead to safety concerns which could be avoided. Using a small motor within the mouth guard is another option that has been considered. The motor would go off when a player's temperature reached a dangerous level, creating vibrations within the mouth. Looking at the image of the cortical homunculus, the tongue is one of the largest areas presented in the picture of the human body. This means that there is a large number of nerve endings on the tongue that would be able to sense the vibrations of a motor in the mouth.

4 Details of Chosen Design

4.1 Mouthguard

For years, oral thermometry has been the gold standard for measuring individual's core body temperature. While other methods such as tympanic membrane or temporal artery thermometry have also been shown to be sound techniques in measuring the core temperature of an individual, oral readings have continued to be proven to work as well or better than other techniques.[10]

Using oral temperature readings have more advantages than just giving accurate readings in relation to the core temperature of the individual. The fact that most football players and many athletes from other sports wear mouth guards means that there is an existing piece of equipment that could have a thermometry system integrated into it. When considering incorporating the thermometry system into the mouth guard, it is important to understand the role of the mouth guard and how pervasively they are used in sports, specifically football.[12]

Mouth guards did not come into wide use in football until the middle of the twentieth century. During these times, the original reasoning for introducing mouth guards was to reduce the number of dental injuries such as chipped or knocked out teeth.[12] While mouth guards have been advertised to have some effect on the risk of concussion, there has been no proof that mouth guards will protect better from concussions. The positive aspect of the mouth guard is that it greatly reduces the risk of dental injuries.[11] Regardless of the exact amount of protection that a mouth guard provides, between 1962 and 1973, all high school and college level football players were required to us a mouth guard that would cover all of the top front teeth.[12] With such wide spread use of the mouth guard, the creation of a thermometry system that is built around a mouth guard could be very useful in tracking core temperatures of athletes.

When looking to integrate the parts of the thermometry system into the mouth guard, the size and dimensions of the mouth guard can affect whether the different components can actually be used. The basic mouth guard for this project would need to be the same design as the mouth guards athletes are choosing. Based on the possibility of incorporating components of the thermometry system directly into the mouth guard, the project would likely require a larger and thicker mouth guard. If components that require less space are used for the project, then there may be more options of mouth guards that have the correct size.

Another aspect that can determine whether this thermometry system can be incorporated is the type of fitting used for the mouth guard. The three main types are called stock, boil and bite, and custom fit mouth guards. The stock mouth guards provide the least amount of protection to the teeth because they come preformed. This means that the product is cheap since they can be mass produced but they are not as well fit to the athlete's teeth and mouth. The boil and bite variation of mouth guards provide a higher level of protection because the mouth guard is fitted to the athlete's mouth. This is achieved by boiling the mouth guard in water and then biting down on the mouth guard to leave teeth impressions.

While this process provides a better fit, if there are components of the system in the mouth guard, biting into the mouth guard after it has been boiled could damage some of these components. The last option is also the most expensive choice. The custom fit mouth guards are made specific to each person based on impressions or mold taken of the person's mouth. The result is a very well fitting mouth guard that offers the best protection.[13] However, since the mouth guards are made on an individual bases, the system would need to be adjusted to fit properly for each mouth guard made. Ultimately, the project requires a large enough mouth piece that is comfortable for athletes to use, while also making sure that the means to form the guard does not offset or break other components of the system.

Based on the fitting requirements for each type of mouth guard listed above, the most viable option is the stock mouth guard that does not need to be custom made for each one and should not have the risk of being crushed when fitted to the individual's mouth. The stock mouth guards are traditionally larger since they do not fit as well with the athlete's teeth.[13] This would offer more space to incorporate components for the device. Moving forward, the project will work based on measurements taken from a stock mouth guard from Shock DoctorTM that is designed for athletes with braces who cannot wear boil and bite mouth guards.

Figure 5: The Double Braces Mouth Guard provides a rough estimate of the dimensions of the mouth guard and the space available for the components of the system. Source: Shock Doctor

4.2 Thermistor

There are many different types of thermistors that are in use for different purposes today. Omega provided a good guide to choosing the proper thermistor. There are three necessary pieces of information that are needed to begin making this decision. First, the right base resistance needs to be found for the application it is being used for. Second, a resistance vs. temperature relationship needs to be specified. Finally, the proper thermistor size and sensor package style needs to be chosen.[14]

4.2.1 Base Resistance

When the temperature being tested for is between -55°C and 70°C, a lower base resistance thermistor is ideal. The body temperature should never get out of the range of 30°C to 45°C so a thermistor with a lower base resistance will work well for this application.[14]

4.2.2 Resistance vs. Temperature Relationship

Thermistors do not have standards that they are associated with their resistance vs. temperature characteristics. Each different type of metal will create a different resistance vs. temperature relationship. Companies will often label a β constant between two specified temperatures on a thermistor so that the relationship can be determined. **??** displays some of the thermistors with smaller base resistances and their resistance change per degree Celsius. It would be ideal to have a larger resistance change per degree Celsius to provide for more accuracy in the temperature readings.[14]

Table 3: Various thermistors with low base resistance values and the resistance vs. temperature relationships. Source: Omega Engineering

Thermistor Model Number	Resistance at 25°C	Resistance Change per °C
44004	2252 Ω	30.7 Ω
44005	3000 Ω	42 Ω
44007	5000 Ω	70 Ω

Typically, the Steinhart-Hart Equation is used to indicate the resistance vs. temperature characteristics for thermistors. Equation 1 shows temperature as a function of resistance.

$$\frac{1}{T} = a + b\ln(R) + c\ln^3(R) \tag{1}$$

Where a, b, and c are constants that are derived from three temperature test points, R is the thermistor resistance in Ohms and T is the temperature in Kelvin.[14].

4.2.3 Size and Sensor Package Type

In order for the thermistor to be placed within a mouth guard it needs to very small in size. In addition, the thermistor will be exposed to the wet environment of the mouth and therefore should be waterproof. Omega creates waterproof thermistors by using closed ended tubes, and specially designed housings. In order for a thermistor of this type to work properly, a sufficient thermal path must be created to the thermistor and the thermal mass needs to be as small as possible.[14]

Omega also creates surface sensing thermistors. In the application being considered, the thermistor would be in direct contact with a surface of the mouth. Omega creates a particular series of surface sensing thermistors. The design includes a thing, round metal stamping into which the thermistor is epoxied. The metal stamping can then be attached to the desired surface to be monitored.[14]

Based on current research, the most practical resistor for this application would be a ON-909-44034 thermistor. This thermistor is epoxy encapsulated and is contained within Stamped, 300 Series stainless steel housing. These thermistors were made to have maximum surface contact. The specs for this thermistor are in 4.[14]

Table 4: This thermistor has many of the characteristics necessary for the current application. Source: Omega Engineering

Model No.	Resistance at 25°C	Interchangeability at 0 - 70°C	Max. Temp.	Tip Diameter
ON-909-44034	5000 Ω	±0.1°C	75°C	0.38

This thermistor allows for the best accuracy, while still measuring the surface temperature in the desired range for this application.

4.3 Vibrating Motor

Precision Microdrives offers a wide variety of vibration motors that might be applicable in both the cases of the mouth guard and the helmet. In the case of the mouthguard, operating under the assumption that the environment within the mouthguard will have moisture would require an encapsulated vibration motor. Precision Microdrives claims that their model 306-108 is the smallest encapsulated motor on the market, with 7 mm in diameter and 24.5 mm long, excluding two flying leads. Typical operating requirements are 44 mA and 66 mW, and the motor is nominally rated at 1.5V for power by either single cell alkaline or nickel batteries (1.2-1.5V). The 7 mm diameter might be too thick for the mouthguard, with thicknesses often reported at 3-4 mm. However, if the motor is to be entirely enclosed by the plastic and thus have no requirement of waterproofing (a tall order), Precision Microdrives also offers motors with flying leads with diameters down to 3 mm, which might fulfill the physical space requirement for mouthguards.

4.4 Battery

For a self contained system in the mouth guard, size is a central factor. To mitigate risk, the safer option is to have the battery imbedded in the strap of the mouth guard, which is outside of the athlete's mouth. The idea is that the athlete will not be able to accidently bite down into the battery if it is encased in the strap outside of the mouth. However, this greatly limits the amount of space for the battery. Cylindrical batteries would easily have a high enough capacity to power a system that only draws 15 μA while recording the temperature.[24] However both the disposable and rechargeable batteries of this variation would be too large.[24]

The size requirement means only button and coin cell batteries could fit. Again there are options for disposable or rechargeable batteries. These batteries have significantly lower capacities but are able to power an average thermistor for enough time to ensure the system is working throughout the season.

$$Thermistor\,draw : 15\,\mu A \tag{2}$$

$$Capacity\,of\,a\,standard\,button\,battery : 24\,mA * h \tag{3}$$

$$Battery\,lifetime = \frac{thermistor\,draw}{battery\,capacity} = 1600\,hr \tag{4}$$

Based on measurements of the strap used for mouth guards, the diameter of the button cell battery should not exceed 12 mm. Panasonic makes two series of rechargeable button batteries that are good at supporting low drain devices over a long period of time. These two battery series have a manganese lithium or a manganese titanium lithium chemistry.[24] However, like other rechargeable batteries, they have a smaller capacity than their disposable counterparts of the same size.[23] This means in order for the rechargeable button cell batteries to power the generalized device for a full season, the diameter would have to be larger than the 12 mm cut off.[24] Since the rechargeable batteries are not an option, for the mouth guard sensor, a piezoelectric system to charge the battery is no longer viable.

With only the disposable button cells as our options, the possible chemistries are the silver, alkaline, mercury, or zinc-air button cells. While the zinc-air variety has the highest capacity, it discharges quickly because the battery will continue to run until it no longer can reduce oxygen from the environment. Silver and mercury button cells both have similar capacities. They also have size varieties that meet the requirement for the mouth guard and have enough power to run the entire season.[24] However based on the safety of the material used in the chemical reactions, the silver button cell is less harmful. In the end, the silver oxide button cell battery has the capacity to deliver the needed voltage and current for a standard thermistor, meets the size criteria, and has the safest materials for batteries of its size.

5 Updated Project Organization

5.1 Design Schedule

For the progress presentation, initial analysis was done on the necessary method of temperature reading, type of alert system to be used and type of power source that would be needed for this application. Moving forward, research will be done into specific thermistors, vibrating , and batteries that will make the system function best. CADD designs will be used to make sure that all components of the system can be integrated into current mouth guard designs. Circuitry will need to be designed to connect all the components of the system. A DesignSafe analysis will be done in order to make sure the product is safe for the user.

5.2 Team Responsibilities

All team responsibilities have been divided between team members. Grace worked on researching the different locations available to sense a temperature and different methods used to sense temperatures. Grace will continue to look into the specific type of thermistor that will be best for a mouth guard temperature sensor. Norman researched types of alert systems that can be used to warn a player when their core body temperature is reaching dangerous levels. Norman will continue his research and find the best vibrating motor to be used in the mouth guard. Tyler researched what the ideal power source would be to make all the components work. Tyler will continue his research and find the best battery to be used in the mouth guard that will be able to power all components in the system.

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