SENIOR DESIGN PRELIMINARY REPORT

Helmet Temperature Sensor Project

BME 401

Grace Murray, Tyler Perez, and Norman Luc
Client: Biju Mathew and Marc Schmidt, Jarden Team Sports

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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 US.[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] Figure 1 shows that since 1975, the number of heat-related deaths in sports has increased. Mortality rate and organ damage from heatstroke are directly related to length of time between core temperature elevation and initiation of cooling therapy.[2] Therefore, heat illness and heatstroke are preventable with an accurate monitoring device that can indicate when a player is in danger.

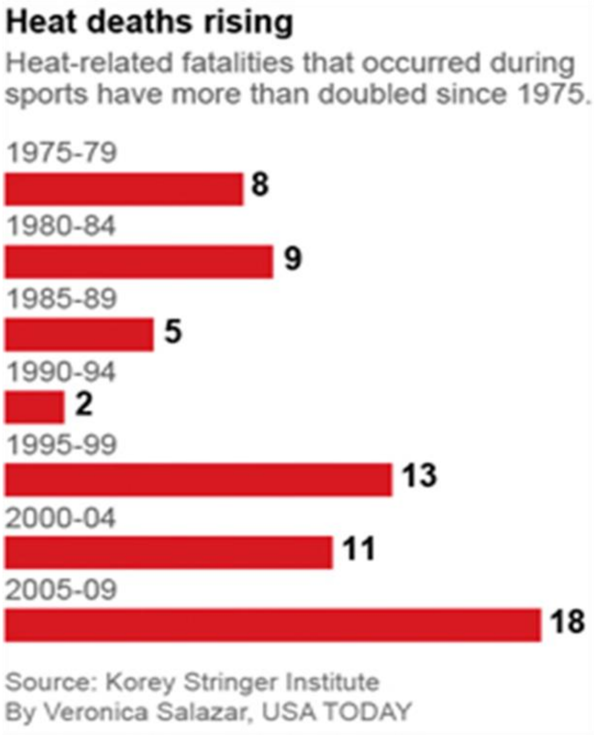


Figure 1

Background

There are five different stages of heat illness that a person can experience. Figure 2 illustrates the progression of stages from least to most severe. Heat edema, the first stage, often occurs when a person is not properly acclimatized to the environment. The person experiences peripheral vasodilation and orthostatic pooling of the blood. The second stage of illness is heat cramps. When this happens, the skeletal muscles in the arms, legs, and trunk begin to spasm uncontrollably. The third stage is heat syncope where loss of consciousness begins to occur. In the fourth stage, heat exhaustion, a person loses the ability to continue exercising. This stage has been defined as when the core body temperature is between 38°C and 40.5°C. The final and most dangerous stage of heat illness is heatstroke. In this situation, the core temperature becomes so high that body tissue and organs suffer damage. This stage occurs when the core temperature of a person is above 40.5°C.[2]

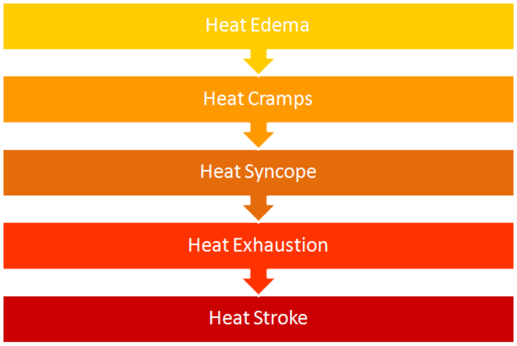


Figure 2

Project Scope

The purpose of this project is to produce a feasible design for a system that uses sensors to measure a player’s core temperature from the temporal artery or from an oral temperature reading. This system is to be installed in a football helmet or mouth guard and will alert the player if he or she is overheating. Being able to accurately measure core temperature in a timely manner could allow players to get immediate treatment and therefore greatly reduce heat-related incidents.

The final system will incorporate small sensors into the helmet and padding or in the mouth guard to monitor core temperature based on readings taken from the head or mouth respectively. Research will determine the best location for the sensors and the number of sensors required to capture an accurate core temperature reading. In the case that a player overheats, the system will be able to alert him or her to cease activities and seek immediate medical attention. Algorithms will be developed to correlate the readings from the temporal artery or mouth guard with accurate core temperatures. The system will be designed to account for variance in the level of skin moisture. The power source used will be able to last the length of a season without being recharged. The system must not compromise the protective integrity of the helmet or mouth guard and must meet current industry durability standards for repeated impacts.

Design Specifications

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 38º C, which has been shown to be related to the onset of heat exhaustion. Any temperatures recorded at higher than 40.5º C indicate 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 to take temperature readings needs to be able to function for a complete season without replacement or recharging. For the system to be working correctly throughout the season, the system must operate for 25 weeks where the system is in use for 20-25 hours per week. These time requirements should provide a sufficient margin to account for both preseason and postseason activities. A significant factor in the consumption of energy is the frequency with which temperature readings are taken. Because of the extreme variation of the progressions of heat illness based on environmental and individual factors, a temperature should be taken every minute to ensure the subject is healthy enough to compete. Depending on whether infrared or thermistors are used in the sensors, multiple readings may be taken at each minute mark and averaged to give a single output temperature. Another factor in the consumption of energy in the system would be the presence of multiple sensors. While oral thermometry in the mouth guard would likely only require one sensor, a system integrated into the helmet might need an average of readings from more than one location. Another design requirement would be the system's ability to run an algorithm that relating the direct readings to the core temperature of the subject. For oral thermometry, the complexity of calculations would not be as high as those required for temporal thermometry.

When integrating the system into current equipment, the system cannot compromise the protective qualities of the equipment. For oral temperature readings, the system would need to be integrated into the mouth guard of the athlete. Currently, testing standards do not exist for mouth guards, even though they are sometimes required for athletes. Most athletic mouth guards require the mouth guard to be heated and then be bitten by the athlete to get a close fit. In this case, the system would either need to be able to work after this fitting process, or the athlete would need to have the mouth guard, complete with sensors, custom made after getting an impression of the athlete's teeth.

If the system is designed to take temporal temperature readings, then the sensors and other components would be built into the helmet. The sensors would be installed in the front pads that contact the forehead and side of the head. The helmet with the built-in system would then need to pass the standard performance specifications for newly manufactured football helmets, as laid out by the National Operating Committee on Standards for Athletic Equipment (NOCSAE). The tests will be performed with a head form in the helmet without a face mask, where the helmet is dropped from a height of 60 inches to achieve acceptable free-fall. The specifications for these tests state that on any of the 16 drop tests, including the heat treated test, the readings for helmet may not result in a peak severity greater than 1200 on the Acceptable Severity Index (SI).[5,6] The SI index is defined by Equation 1.[4] There can also be no un-restorable loosening of the fit as described in Section 20, NOCSAE DOC.001. The drop would be performed in all of the positioning shown in Figure 3.[6]

$$SI = \int_0^T a(t)dt$$

Equation 1: The Severity Index (SI) is the time integral of the acceleration of the head during an impact.[4]

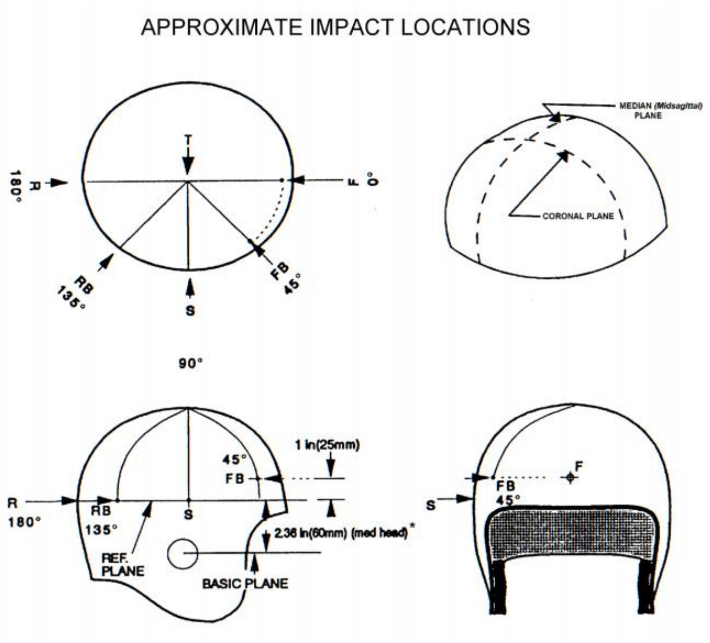


Figure 3: This figure shows the locations that the helmet must be dropped on in testing in order to meet NOCSAE specifications.[5]

In the end, the important design requirement is that the system is accurate enough to detect temperature to within 0.1° C. The system must fit inside current football equipment. The weight of the components should not cause a noticeable difference in the helmet’s weight distribution and position of the helmet on the subject. The warning signal should be able to easily alert the subject that he or she needs to seek medical attention. This would be an alarm in the range of 70-75 decibels (dB). The final product should be easy to use by subjects with limited knowledge of the product and should not be invasive. More specifically, the system should not create a risk of accidentally injuring the subject. 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 1200 SI, and given the moist environment inside the helmet, the system should also be waterproof. Table 1 summarizes these requirements. At this point in time, the cost of the product is not a concern since a proof of concept is more important.

Table 1: The general requirements for the final product based on industry requirements and client expectations.[5,6,7]

Specification	Requirement
	All components fit in existing equipment
Weight	Light enough to not alter equipment's position
Audible	Alarm is easily heard by subject
Accurate	Detects to .1° C
Reliable	Limited false alarms
Durable	Can continue operating after an impact of 1200 SI
Cost	No requirement

Existing Technology – Monitoring Core Temperature in Athletes

Hot Head Technologies, Inc.™

Hot Head Technologies has produced a device, shown in Figure 3, which has the ability to continuously measure the forehead temperature during physical activity without disrupting the integrity of the helmet.[8] That product is a small pad that uses a thermal sensor and is placed in the upper quadrant of the helmet between the temple and the forehead.[9] Hot Head's technology uses radio frequency identification (RFID)-enabled heat sensors to transmit the information collected to the sidelines.[10] A previous study done on the technology found that there was a correlation of 0.801 ($R^2=0.64$, SEE=0.25, p=0.00) between the device developed by Hot Head

Technologies and core temperature as measured by a rectal thermistor.[11] Hot Head's device was able to predict the core temperature more accurately than any other previous methods.

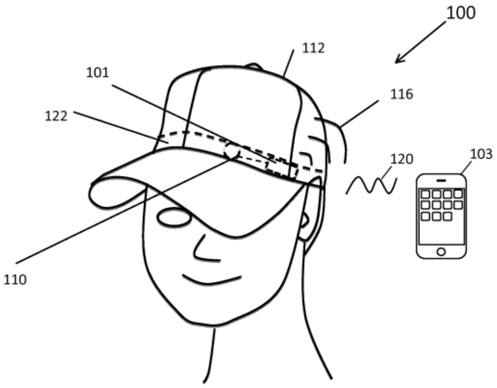
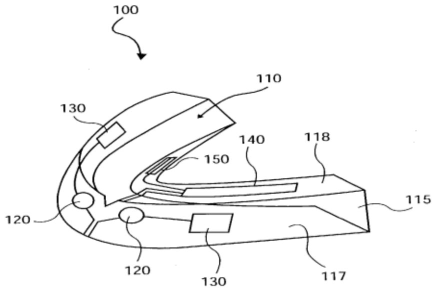


Figure 3. A system designed to monitor biological data using the sensor pad (110) and the biosensor assembly (101), which send an alert (116) along a path (120) to a secondary device (103).

However, Douglas Casa, director of athletic training at the University of Connecticut, is not convinced that this technology is completely accurate and noted, "We've been doing studies with heat for 20 years, and we can't find where skin temperature correlates with core temperature."[9] It is important that the product to be to be designed and produced is one that the sports community supports and believes will improve the well-being of their athletes.

Mouthpiece Monitor

A system has been designed to monitor a subject's core temperature during physical exercise using a mouthpiece, as shown in Figure 4. The mouthpiece contains a temperature sensor that reads the subject's core temperature and transmits the data to the processor. In the processor, the data is analyzed using a predetermined set of criteria. If the temperature passes a certain set threshold, an alarm is activated to alert the subject of the high temperature. If the alarm is not triggered, the mouthpiece continues to monitor the subject.[12]



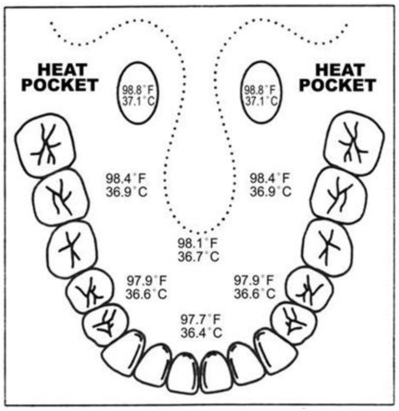


Figure 4 (left). A mouthpiece monitor with power sources (130), temperature sensors (120), a processor (140), and an alarm (150). **Figure 5 (right).** A heat map of varying temperatures within the mouth. Mabis Healthcare: http://www.mabisdmi.com/.

This method of measuring temperature does have its advantages, as it can read quick changes in core temperature and the method of acquiring the core temperature is easily accessible. However, oral temperatures collected tend to be lower than actual core temperatures. Additionally, as Figure 5 shows, the temperatures at different locations within the mouth cavity can differ with the back of the mouth being warmer than the front of the mouth, leading to inconsistent measurements of core temperatures. This method could also cause issues when used in athletes, since readings would be affected by food and liquid intake as well as changes in breathing.[3] As athletes often have varied breathing rates, depending on the level of exertion, and consume liquids to stay hydrated, this method does not seem to be a practical way to acquire and calculate accurate core temperatures in athletes. Another factor that would negatively impact temperature readings is the tendency of athletes to remove mouth guards between plays, both in games and in practice. As such, the drastic change in environment between the mouth and the ambient surroundings experienced by the sensor could skew readings. Additionally, if the sensor is taking readings at a certain rate, then there exists the possibility that readings could be missed while the mouth guard is not in proper position or not in use.

Miscellaneous helmet thermometry

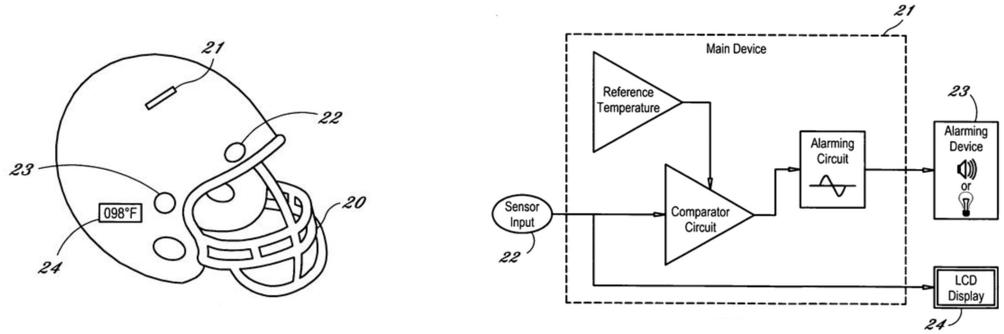


Figure 6. The location of components of a helmet temperature sensing patent (left) and a rough process diagram of the device (right).[13]

Current patents show that other individuals or entities have considered the use of a thermometry system that monitors subjects and other people at risk of heat illness. US patent 20070177651 A1, filed in 2006, proposed a system that would take temperature readings from the forehead that could then be related to the core body temperature. In this case, the proposed system would consist of sensors that could be attached to the forehead of a helmet. These sensors would use thermistors, which are resistors whose resistances greatly vary with temperature. The idea would be to use the difference between current readings from the sensors in comparison to known safe readings, with an alarm being triggered if the difference is at or above a certain amount. Given that these readings relate to skin temperature, it is important to note that in a 1998 study, measurements from thermistors were proven to vary within a range of 1.3º C, which could lead to imprecise readings.[15] Figure 6 shows the location of the components in the proposed design as well as the rough circuit diagram for the system.[1]

Another patent, 20120265477 A1, was filed in 2012 for a helmet that could record a wide array of metrics.[14] This list includes temperature, humidity, heart rate, and movement. The invention is described as using two different systems, one that monitors temperature and one that monitors for impact events. The temperature monitoring system is based on using a comparison between readings from the sensors and a predetermined threshold. Should the sensor reading be greater than the threshold, information would be sent wirelessly to a remote location. Again, the temperature readings were based on skin temperature, though the ability to detect skin temperature of the subject was not the focus of this invention.

Temporal Scanner

The Temporal Scanner^{TM}, US 20110092822 A1, made by Exergen Corporation, is designed for both medical and household use as a means of measuring the core temperature based on readings from the temporal artery.[16] Figure 7 shows the superficial temporal artery from which the scanner reads the temperature. Arteries represent direct paths of heat transfer via blood flow from the heart, where the core temperature measurement is most accurate. Temporal artery thermometry thus provides a reading from an artery at a point very close to the skin, resulting in an accurate representation of the core temperature. The scanner takes temperature readings at a sampling rate of 1000 Hz while the sensor is swiped from the forehead to the temple. A thermopile detects the thermal energy and converts it to an electrical signal. The highest temperature corresponds with the temporal artery, where the blood temperature is higher than that of the surrounding tissue and correlates closely with the core temperature.

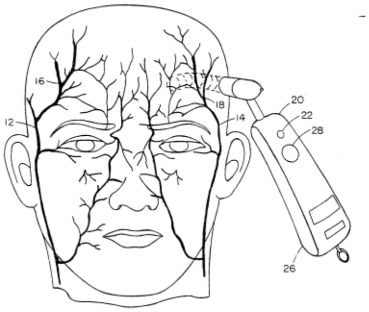


Figure 7. The location of the temporal artery in the face, and the portion of it from which the Temporal Scanner measures temperature.[16]

Using the heat balance equations defining heat transfer from the core to the skin and heat loss from the skin to environment yields the 2 equations

$$q = wc(T_c - T_s) \text{ and } q = hA(T_s - T_a) \quad ,$$

Where q is heat flow, w is blood mass flow rate, c is blood specific heat, A is surface area, T_s is the surface temperature, T_a is the ambient temperature, T_c is the core temperature, and h is an empirically determined coefficient describing the radiation between the skin and the surroundings. Equating and dividing both sides by the surface area A gives

$$pc(T_c - T_s) = h(T_s - T_a) \quad ,$$

Where w/A is defined as p, the perfusion rate. Rearranging the terms to solve for the core temperature gives

$$T_c = \tfrac{h}{pc}(T_s - T_a) + T_s \quad ,$$

Which can be written as

$$T_c = \left(1 + \frac{h}{pc}\right)(T_s - T_a) + T_a \quad .$$

In this form of the equation, a maximum value of p leads to the core temperature being closest to the surface temperature reading. Since the perfusion rate is highest where the temperature is highest, i.e. in the presence of the temporal artery, the highest temperature acquired during a scan corresponds with the most accurate representation of the core temperature. Although the exact form of the equation is fourth-order due to the radiation factor, this linearized form provides excellent accuracy over the temperature range of interest of about 90° to 105° F (32° to 41°C).[16] As such, a sensor using the same or similar technology to measure thermal radiation should be able to accurately determine the core temperature from the surface temperature reading, the ambient temperature, and predetermined constants.

Current Organization

For the current team organization, Grace will be in charge of giving the preliminary presentation, while working on finding existing solutions relating to temperature sensors, and completing the DesignSafe assignment. Norman will be in charge of giving the progress presentation, while working on finding existing solutions relating to Exergen infrared technology, and completing the creation of the product website. Tyler will be in charge of giving the final presentation, while researching project specifications and completing work on sensor location and doing CAD design.

Project Schedule:

	September					October				November				December	
Tasks	1	8	15	22	29	7	14	21	28	3	10	17	24	1	8
Team/Project Selection	🟩	🟦													
Project Scope		🟩	🟦												
Preliminary Literary Search		🟩	🟩	🟩	🟦										
Preliminary Report and Presentation			🟩	🟩	🟦										
Design Options				🟩	🟩	🟩	🟩	🟩	🟦						
Web Page					🟩	🟦									
DesignSafe						🟦									
Progress Report and Presentation							🟩	🟩	🟦						
Final Design								🟩	🟩	🟩	🟩	🟩	🟦		
Final Report and Presentation											🟩	🟩	🟩	🟦	
Poster													🟩	🟩	🟦

Week of work	🟩
Week of completion	🟦

Figure 8: The design schedule for the project is shown above and indicates the week(s) of preparation for a task in green and the week of completion in blue.

Moving forward, the possible design options will be explored by the team. This will include the final decision on whether to focus efforts on the development of the system in the helmet or mouth guard. The project website as well as the DesignSafe analysis of the system will be executed in the next week. The next major report will present the results from investigating different designs and the final design for the project.

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