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SMART FOOTBALL HELMET

WPI Major Qualifying Project

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Smart Football Helmet

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Report Submitted to:

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Abstract

Concussion protocols in contact sports are limited by the undetectable nature of concussions post-impact. One way to assure injuries are addressed is to know how much change in rotational acceleration the head undergoes at the time of impact. This gives medical professionals a stronger foundation to assess the risk of injury from an impact, improving diagnostic ability and decreasing players' risk for CTE, a degenerative and fatal brain disease. This project set out to create a helmet that used sensor data in head injury criteria equations to alert a wearer to possible concussions. A helmet was equipped with force sensors, an accelerometer, a microprocessor, and a Bluetooth chip and demonstrated wireless communication of data to a database on a server. This data was filtered and analyzed with head injury criteria and communicated with a website that displays the information and sends real-time alerts when there is a risk of injury.

Introduction

Concussions affect millions of people every year, with one poll finding that one out of every four Americans has had a concussion at some point in their lives (Hensley, 2016). On top of this, it is estimated that 50% of all concussions go undiagnosed and untreated (*Concussion Statistics and Facts | UPMC | Pittsburgh*, n.d.). The current diagnostic procedure for concussions relies heavily on subjective information from the patient, and the injuries are not always detectable through these procedures. When concussions are left untreated, they can cause a wide range of issues from mental deficits and personality changes to seizures and brain herniation (Crosson, 2015). Out of the millions of sports-related concussions that occur in the U.S. each year, the majority of them are from football (Harmon et. al, 2013). 2 out of every 10 high school football players will sustain a concussion every year (Crosson, 2015). The rise of chronic traumatic encephalopathy (CTE) appearing in football players has also brought the sport's safety into question. CTE is a progressive and fatal neurological disease, currently only diagnosable postmortem, and is thought to be caused by repeated injuries to the brain. Early stages of the disease can cause migraines, depression, and short-term memory loss. In the later stages, it can cause more severe executive dysfunction and cognitive impairment, aggression, dementia, and death (Jowers, 2022). In 2019, a study concluded that for every 2.6 years a person plays American football, their risk of developing CTE is doubled (Mez et al., 2020). Additionally, a 2017 study conducted on the brains of deceased NFL players found CTE present in 99% of them. This fatal disease poses a risk to all American football players and currently has no cure.

Smart helmets that have been emerging in recent years allow football players to know just how much force an impact caused on their heads. With the new development of sensor-equipped helmets, sensors can track the movement, change in acceleration, and forces acting on a user in real-time, helping to notify when a risk of concussion may be present. These sensor-equipped helmets could help in determining the risk of injury, improving the diagnosis of concussions, and could refine post-injury recovery practices, lessening the long-term effects of concussions.

The goals of this project were to design, develop, and test a smart helmet prototype system that can connect to the internet and provide real-time notifications of possible injury-causing impacts. The smart helmet prototype did not have the goal of diagnosing a concussion, but rather improving how often players will be examined for a concussion from impacts presenting enough force and acceleration to cause one. There are many aspects to consider when designing a smart wearable football helmet, as the protection and safety that the helmet provides also must not be compromised through the addition of sensors. This is not always feasible for an initial prototype but is still a consideration to be factored in throughout the design and development processes. The prototype was to be wireless, operable for at least the length of time of a regular football game, and able to handle and sense the high end of ranges of accelerations and forces from impacts determined to have the ability to cause a concussion. The data from the sensors had to be transmitted at a rate of multiple readings per second through a secure wireless network to be displayed on a user interface accessible to players and updated in real-time. The risk of concussion from an impact was to be determined through the use of head injury criterion and presented to the user in categories from mild to severe risk of injury.

These goals were accomplished through a series of tasks, starting with researching different methods of measuring the risk of concussions to decide which were most useful and feasible for this project. When the method of concussion risk assessment was decided, sensors and microcontrollers were researched to determine the necessary requirements to pick the most relevant and affordable technology to use. The helmet was then assembled with this technology, and the microcontroller was coded such that the data from these sensors can be viewed during testing. The physical testing of the smart helmet prototype was done using a pneumatic horizontal linear piston to deliver measured impacts to the helmet at four different locations. These impacts were delivered at three different speeds at each location, with three trials for each speed, for a total of 36 impacts. This data was then used to determine how filtering would be done on the final prototype to reduce noise and improve accuracy in the recorded data. A server was coded onto an external microprocessor-based miniature computer to receive the data through a Bluetooth connection with the microcontroller on the helmet and store the data in a local database on the miniature computer. A web server, separate from the first server that adds the data to the database, was also connected to the miniature computer and was linked to a website template to display data from impacts that posed a risk for injury in real-time. The risk of injury was calculated through head injury criteria to display the severity of the impacts on the user.

Background

Humans have been using helmets to protect their skulls for centuries, but only recently were helmets incorporated into sports. Football helmets were not used until the 1890s, after a rise in head injuries resulting from significant blows during games (Levy et al., 2004). Initially, helmets were made of leather but did not offer much protection due to an inability to absorb a great deal of force. Plastic helmets soon took over going into the 1940s, and then padding was added in the decades after, subsequently followed by facemasks (Stamp, 2012). In recent years, football helmets have had technological advances with in-helmet sensors to track impacts.

Smart wearable devices are a new generation of athletic equipment that improve the safety of athletes competing in contact sports. Helmets with sensors can be used as a non-invasive way to record data on the impacts that the player's skull sustains. This data then can assist in concussion diagnostics and be used for risk assessment for players. Evidence shows that repeated mild traumatic brain injuries (TBIs) can be more harmful in the long term than moderate and severe TBIs. These mild TBIs can often be caused by impacts sustained that are not traditionally seen as harmful (Traumatic Brain Injury & Concussion: Repeated Head Impacts, 2021). With smart helmets, players can have their injuries tracked and assessed for them. By knowing how severe an impact was, the risk of damage to the brain can be estimated, and proper medical treatment can be put in place to minimize the risk of long-term damage.

Concussions are a type of mild TBI caused by sudden acceleration and deceleration of the brain from biomechanical forces that causes a pathophysiologic response (Kutcher & Giza, 2014). While concussions are often associated with a hit to the head, an impact on the skull does not necessarily need to occur for one to have a concussion. Any sudden change in acceleration of the head can cause one. The symptoms of a concussion can vary, with the most common symptom being a headache. The more obvious signs of a headache are loss of consciousness and amnesia, but loss of consciousness occurs less than 30% of the time and amnesia only occurs up to 50% of the time in TBIs (Kutcher & Giza, 2014). The symptoms can sometimes be correlated to an acute migraine which can make concussion difficult to diagnose.

Currently, the National Football League (NFL) has a five-step protocol they use to assess a possibility of a concussion on a player who is suspected to be injured (Axson, 2022). Although this protocol was developed by physicians, scientists, and an independent board, these protocols are changed fairly frequently, with the last update in July 2020 (Axson, 2022). However, the symptoms of a concussion do not always present themselves immediately after the impact (Concussion Signs and Symptoms, n.d.). This is an issue as the NFL Head, Neck, and Spine

Committee's protocol is to pull the player from the game if they display any symptoms, but if the symptoms do not immediately present themselves, the player can continue to play (NFL Concussion Diagnosis and Management Protocol, n.d.). The NFL also has it so that if the player has undergone an examination, they also need to go to a follow-up examination the next day. However, it is possible that symptoms will not present themselves even after a day.

The current assessment of whether a player has experienced a concussion also heavily relies on the player reporting their symptoms, meaning concussions can go undiagnosed if players do not want to be taken off the field. This applies to professionals and adolescents, as 47% of young adults do not report their sports-related concussion symptoms (Sports-Related Concussion, n.d.). Medical professionals must depend on observations of the player's behavior, as there is no quantitative way to medically diagnose a concussion after the impact has occurred (Kutcher & Giza, 2014). Undiagnosed concussions are dangerous and further physical activity can damage the neurological functions of the brain (Kutcher & Giza, 2014).

While current smart helmets do not necessarily aid in the diagnosis of concussions, they do give immediate feedback on the possible severity of the forces and changes in acceleration that are acting on the brain from an impact. This data could assist in concussion assessment and help determine the proper next steps of care, and at the least give players immediate notice when they may have been subject to concussion-causing forces. Promptly alerting the high possibility of a concussion eliminates the risk of players further injuring themselves by continuously playing and undiagnosed concussions.

Head Injury Criteria (HIC) is often used to determine the possibility of a head injury, and it is often used for crash scenarios (Hayes et al., 2007). Some studies used HIC to predict the probability of a concussion upon impact only taking linear acceleration into account. However, according to the study, Brain Injury Prediction: Assessing the Combined Probability of Concussion Using Linear and Rotational Head Acceleration, done by Steven Rowson & Stefan M. Duma, the linear acceleration of the head had an insignificant correlation with the probability of a concussion. They created a combined risk function to calculate the risk of a concussion using both rotational and linear acceleration. It was found that rotational acceleration was the main factor in the likelihood of a concussion (Rowson & Duma, 2013). HIC is also more commonly used for severe head injuries. For mild TBIs, like concussion, Generalized Model for Brain Injury Threshold (GAMBIT) or Head Impact Power (HIP) can be used which takes into account both linear and rotational acceleration and would be ideal to use in the prediction of a concussion (Rowson & Duma, 2013).

Rotational acceleration has more of an effect on the brain than linear acceleration because of the shear forces generated. The brain tissue is more vulnerable to shear forces than other biological tissues in the body, so rotational acceleration can cause brain tissue damage (Meaney & Smith, 2011).

It was found that the mean peak resultant rotational acceleration that caused a concussion is between 5000 and 8000 rad/s^2 based on the comparison done by McIntosh and Patton, etc. (McIntosh et al., 2014). The large range is due to the different sample sizes and the different types of studies done whether it was only analyzing recorded concussion-causing impacts or testing all impacts. While there is no set resultant peak, a general range can be found as seen above, so there is some correlation between rotational acceleration and the probability of a concussion.

From observing this correlation, the team created a sensor-equipped football helmet that can detect risk for possible TBIs as there is currently not a sufficient quantitative way to diagnose a concussion. To do this, the team created a sensor-equipped football helmet that can detect risk for possible TBIs through the use of accelerometers, force sensors, and a Bluetooth chip that sends data to a companion web server and database. A microprocessor will also alert coaches and trainers in real-time that a player on the field was involved in a collision that had a high probability of causing a concussion. The system will improve player safety by reducing the number of players who unknowingly experience concussion-causing forces during a game or practice. Although not a diagnostic tool, the smart helmet could assist in having concussion protocols intervene more often for potentially harmful impacts to allow medical professionals to assess and prevent a player from playing on and worsening a possible brain injury. By alerting players to a potentially injurious impact and having them be evaluated more often for concussions, treatment can be implemented much sooner to give the brain as much of an advantage in healing as possible. The following sections describe the different steps taken to develop a system that can detect a risk of a concussion from an impact and communicate significant risks to the wearer. The project aims to fill the procedural gap that existing helmets that can receive impact data do but do not update in real-time. To do this, the Smart Helmet will receive data and predict the probability of an impact causing a concussion in real-time. This is followed by the results from the system being tested for accuracy in measuring the forces and accelerations during impacts, compared to other helmet test data from the literature. This report ends with a discussion of recommendations for any future iterations of this project, such as consolidating circuit components and simplifying data transmission from the helmet sensors to the user interface.

Methods

The team developed a number of methods to meet five main objectives:

Objective 1: Design Iterations

Objective 2: System Assembly

Objective 3: Determining Risk of Head Injury

Objective 4: Data Transmission

Objective 5: Physical Testing

The first objective was to research different methods of designing a concussion risk assessment device for football players and the different technologies that could be used in these devices. The second objective was to take the decisions from the first objective and physically wire the circuitry and apply the sensors to the helmet. The third objective was to use a mathematical model in order to determine the risk of head injury that can be used with the data collected in the following objectives. The fourth objective was to wirelessly transmit the data from the sensors on the helmet to a user interface that would display the information in an easily digestible manner. The final objective was to test the device's functionality by delivering controlled impacts to the device to simulate real-world scenarios and compare this data with data from similar testing procedures run on smart helmets for accuracy.

Objective 1: Design Iterations

A goal of this project was to create a device that can detect forces to the head and report the likelihood of a resulting concussion. There were different ideas generated and found during research to achieve this goal. These design options revolve around the base of the device and which sensors were used.

A variation of a smart mouthguard was considered as an option for this project. The mouth guard could work similarly to the design of a smart helmet in the sense that it would receive and send information about the acceleration and impact of a player during contact. This method is ideal in that the accelerations of the head itself can be measured, not just the helmet. This would mean that many small components would have to be implemented within the mouthguard in a manner that would not compromise the safety of the mouthguard or become too bulky to function as it is meant to inside the mouth. This design was not chosen as it would be too expensive to acquire the necessary miniature components and too inhibiting to complete data transmission with a user interface alongside developing mouthguard molding to create a final functioning prototype. It was also believed that the capability to do this was beyond the range of the team's expertise.

An initially favored sensor for the helmet was an electroencephalogram (EEG). EEGs use electrodes around the head to sense electrical activity in the brain. These are one of the most reliable methods of determining if a person has suffered a traumatic brain injury or TBI. Immediately after this occurs, epileptiform activity, described as high-amplitude sharp waves or high-frequency discharges, occurs in the brain which is easily seen with an EEG (Ianof). Although this may have been the most accurate way to detect the probability of head injury, using an EEG would not have been practical for testing. In order to achieve the goals of this project, the helmet has to endure high impact and high change of acceleration, and the use of an EEG requires a functioning brain. Thus, if this design were to use an EEG, it would require human subjects undergoing head trauma, which would not be reasonable or ethical for this project.

Ultimately, the team settled on creating a smart football helmet system. This decision was made because the team felt confident in their ability to create a proof-of-concept football helmet that could achieve the goals of measuring impact, change in acceleration, and analyzing the probability of head injury. The team decided to use a helmet with the necessary components to support the project. Multiple spare Riddell helmets were offered by WPI to utilize for the project, however, it was decided that a new Riddell Speed Classic Icon helmet will be ordered to complete the project instead. The spare helmets were missing interior padding and had other damages as well. Above all, the helmets were not up to the current helmet safety standards that the team desired in order to complete the project in an effective manner. A new Riddell Speed Classic Icon helmet provided the team with a helmet that contains all of the necessary padding and components to complete the project.

Sensors that measure impact were important for the design of a smart helmet. Force transducers made of piezoresistive material allow forces to be measured by measuring voltage drops across the circuit. This was implemented into a helmet to measure the force of impact, but more importantly, used for determining where an impact occurred on a helmet. With multiple sensors implemented into the helmet, impacts could be mapped around the whole helmet with proper placement. This usage of force sensors allowed for the use of sensors with smaller capacities, as the measure of impact was not the primary area of interest. Simply knowing an impact occurred was more important to the helmet.

The decision of using four force sensors was determined for the design of the smart helmet, due to multiple reasons. Multiple force sensors placed evenly around the helmet would allow the location of impact at almost any point on the surface of the helmet to be measured. The exact locations where the sensors would be placed inside the helmet are the crown, both left and right sides, and the top of the helmet. These locations would allow for an even distribution of coverage on the helmet, as well as cover areas that have a higher probability of being impacted by football players.

One cause of damage to the brain during an impact is the change in linear and angular acceleration of the skull. The choice was made to have two accelerometers because this increases the accuracy of the data from the helmet, increasing its accuracy in assessing the risk of injury. However, due to the limitations of the microcontroller, only one could be used. The accelerometer chosen measures both change in linear acceleration as well as angular acceleration, and measures 3 axes, giving a view of how the skull moves in the x, y, and z-directions. With a tri-axial accelerometer that has a high range of measurement, up to 200Gs, it is high enough to record impacts well above the highest thresholds from peer-reviewed research. These studies have estimated the type of impact that a change in acceleration will have on the brain.

The design for the smart helmet prototype started with a Riddell Speed Classic Icon as the base helmet. It was modified so that it could hold an Arduino UNO microcontroller, Bluetooth module, portable battery, and appropriate circuitry to connect the sensors and accelerometer on the back. One accelerometer was attached to the back of the helmet in a separate compartment to keep it firmly mounted on the helmet to measure its movement as accurately as possible. Four force sensors were placed inside the helmet at the crown, both left and right sides, and the back of the helmet. The 3-D printed compartment on the back of the helmet was designed to hold the microprocessor and circuitry and the other 3-D printed compartment seen just under the main compartment that fits flush to the helmet is designed to hold the accelerometer. The main compartment will be attached to the helmet with a mount that allows single-axial movement to prevent the compartment from snapping off. Each compartment also has holes for wiring to attach the sensors in the helmet to the components in the compartments. Each compartment will also have covers that can be secured or removed at the user's discretion. The full assembly can be seen in Figure 1.

Figure 1: Photo of Circuitry Inside Compartment Mounted on Helmet

Objective 2: System Assembly

2.1 Circuit Design

An Arduino UNO Microcontroller was used for this system. This controller was selected because of its multiple analog ports, and there are many open-source Arduino resources readily available from sites such as the Arduino website which allowed the feasibility of programming the board to our desire.

The circuit consists of four force sensors and an accelerometer that measures impact and motion readings and can be read by the Arduino UNO to be recorded and communicated with the components that connect to the web server. The force sensor used in the system is a Flexiforce

Pressure Sensor that can read up to 100 lbs of impact. An image of the sensor can be seen in Figure 2.

Figure 2: Image of Flexiforce Pressure Sensor Used on Smart Helmet Prototype

The force sensor is essential to the system to read not only the magnitude of the impact on the helmet but also the location of the impact. Information on the location of impact allows the team to complete data analysis based on where and when the impact happened. Since concussion research shows a correlation between the acceleration of the head during impact and the likelihood of a concussion, the data analysis of our system relied heavily on the accelerometer for predictive analysis.

The accelerometer used was a three-axis Adafruit ADXL375 accelerometer which had a tolerance of +/- 200g of rotational acceleration. This accelerometer outputs XYZ coordinate data in respect to its orientation. An image of the product can be seen in Figure 3.

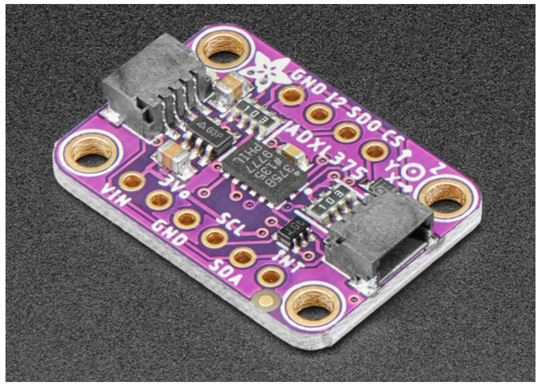

Figure 3: Image of Adafruit ADXL375 Accelerometer Used on Smart Helmet Prototype

The accelerometer provided the majority of the data analyzed in order to determine the probability of the athlete suffering a concussion.

The HC-06 Bluetooth chip seen in Figure 4 was selected for wireless communication. This module was selected as it is commonly used in Arduino projects and was very straightforward for setting up. This Bluetooth chip can also be powered with 5V, so no voltage divider is needed for further complications within the circuit.

Figure 4: Image of DSD Tech HC-06 Bluetooth Module Used on Smart Helmet Prototype

A block circuit diagram (Figure 5) is shown alongside the completed circuit (Figure 6). All components were connected to the Arduino UNO Microcontroller board and powered through its 5V pin, and grounded through the GND pin. The Arduino UNO was powered by a PKCell USB Battery Pack with a 2200 mAh capacity and 5V 1A output. The Bluetooth chip was connected via two digital pins, designated within the program. The four force sensors were measured via wire to individual analog pins so that an individual sensor's results could be recorded. The accelerometer was connected through the SDA and SCL pins. The Arduino Program can be found in Appendix A.1.

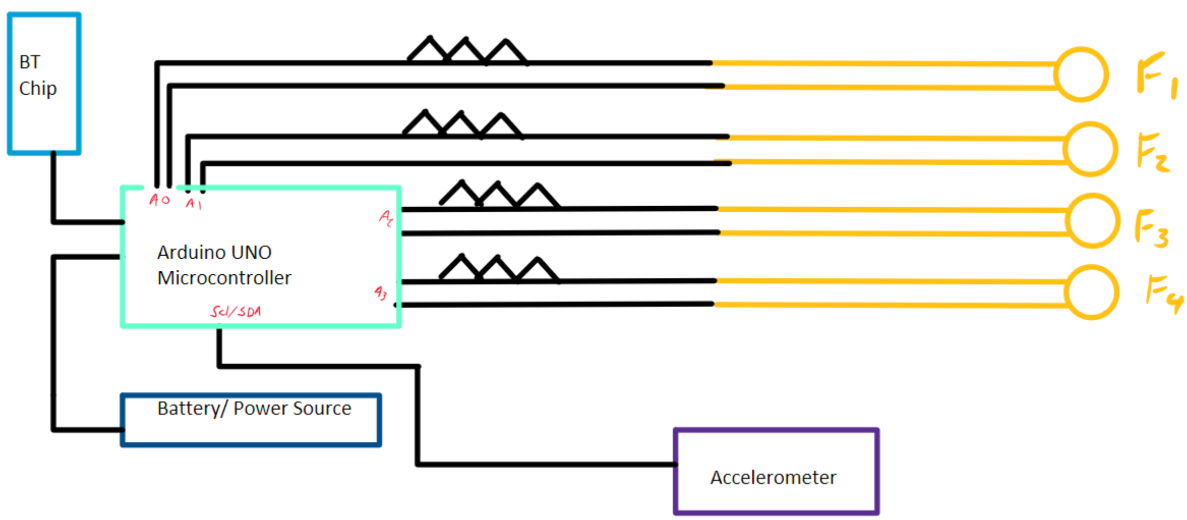

Figure 5: Written Diagram of Circuit Used for Smart Helmet Prototype with Arduino UNO, Force Sensors, Bluetooth Chip, Accelerometer, and Portable Battery

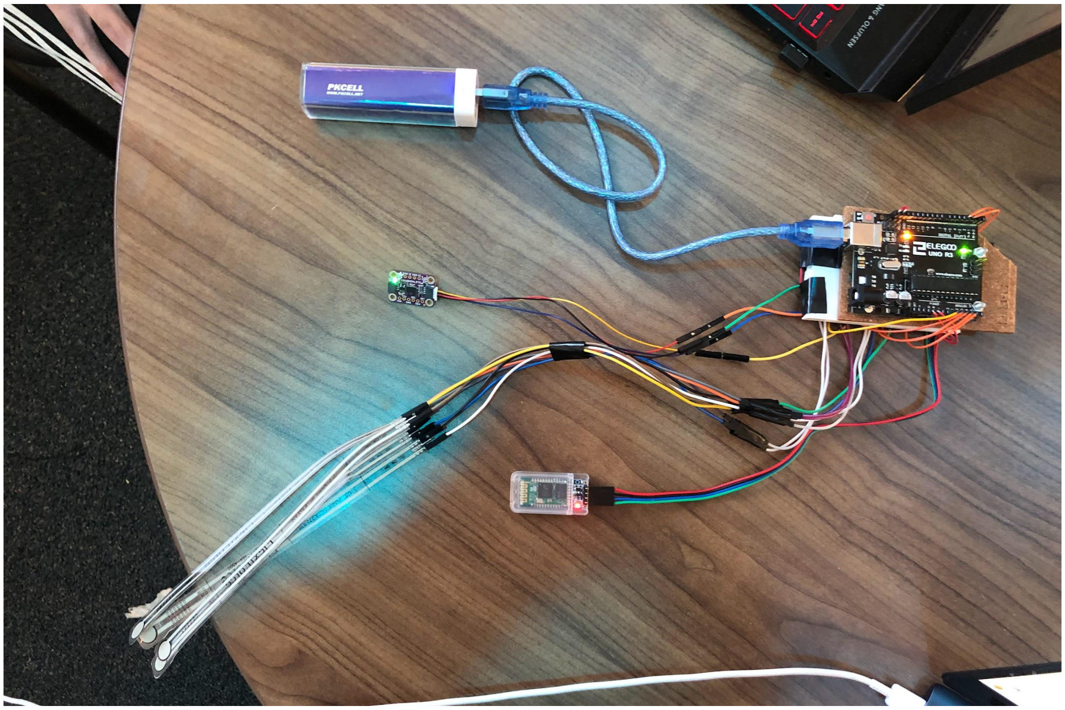

Figure 6: Photo of Accelerometer, Force Sensors, Bluetooth Chip, and Arduino UNO Assembled and Powered with Portable Battery

2.2 Sensor Calibration

The calibration process for the force sensors consisted of placing known weights on the sensor and recording the forces displayed. The known weight values were plotted on the x-axis and the corresponding force value was the y-axis. From the scatter plot, a linear regression that best fits the data was found and used to calibrate the sensors. This provided the team with a better understanding of how functional and accurate the sensors were. The data for these trials can be seen in Table 1. Table 2 shows the calibration curves and the correlations found from the trials. The correlations were found by using the CORREL function in Excel and comparing the array of known weights to the array of forces displayed.

Table 1: Force Sensor Calibration Data

Calibration Data							
Sensor 1		Sensor 2		Sensor 3		Sensor 4	
Known Weight (lbs)	Force (lbf)	Known Weight (lbs)	Force (lbf)	Known Weight (lbs)	Force (lbf)	Known Weight (lbs)	Force (lbf)
0.55	2	0.55	3	0.55	3	0.55	1
0.77	4	0.77	4	0.77	3	0.77	2
0.949	7	0.949	5	0.949	5	0.949	3
1.08	7	1.08	7	1.08	7	1.08	5

Table 2: Force Sensor Calibration Curves and Correlations

Calibration and Correlation		
Sensor 1:	0.0227x-3.65	0.9699078968
Sensor 2:	7.11x-1.21	0.9573463104
Sensor 3:	7.54x-1.81	0.9047793123
Sensor 4:	7.11x-3.21	0.9573463104

An example of the regression scatter plot for Sensor 1 can be seen in Figure 7.

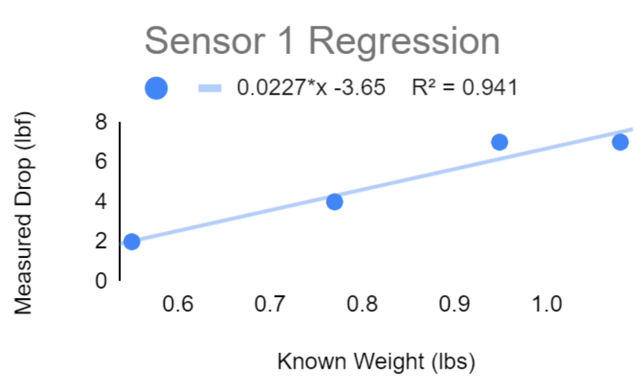

Figure 7: Linear Regression Scatter Plot for Force Sensor One

After analyzing the data from this calibration study, it was evident that the correlation between the known weight being placed on the sensor and the force displayed was strong. This correlation data proved that the sensors' readings were increasing consistently as the weights increased. The linear regressions of the data plots were taken. The team used the regression equation from each sensor plot during data analysis of helmet impacts in order to account for the existent variability of the force sensors and conclude an accurate measurement in units of lbf.

Lastly, the ADXL375 Accelerometer came factory calibrated. The team ran tests to assure no further calibration was necessary.

2.3 Helmet Compartment

The helmet was designed to have two compartments mounted to the back that contained the components that made up the system. One compartment held the microprocessor, the battery, the Bluetooth chip, and a majority of the wiring. The other compartment held the accelerometer and fit flush to the helmet to mimic the movements of the player's head as closely as possible. The compartment that held the majority of the components was 6.25 inches long by 3.75 inches wide and 3 inches high. The width dimension does not account for the extension on the back which allows it to connect to the helmet, which adds another 0.70 inches. The compartment can be seen in Figure 8.

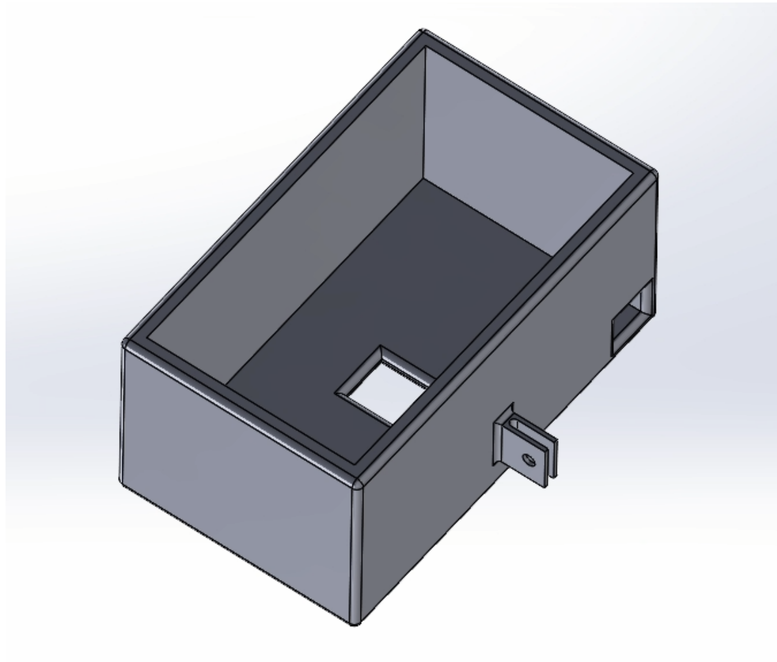

Figure 8: Computer-Aided Design Capture of Compartment to Store Microcontroller and Battery Externally on Helmet

The compartment in Figure 8 had a hole in the back for wires to feed out of and into the helmet. There was also a hole in the bottom right corner for the accelerometer wiring to feed out of into its own compartment.

The accelerometer compartment was 1.25 inch x 1.00 inch x 0.63 inches and sat flush against the back of the helmet just below the main compartment. The compartment had a hole for the accelerometer cable to feed through from the Arduino UNO compartment. This compartment can be seen in Figure 9.

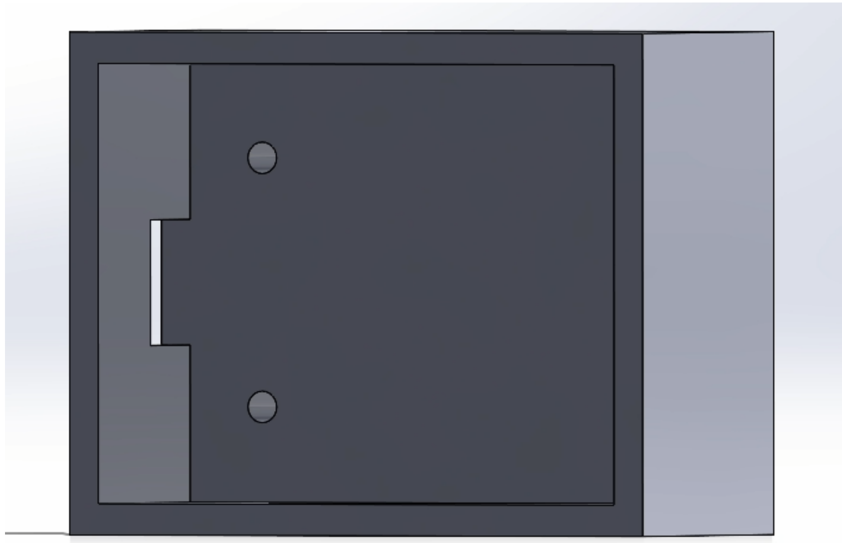

Figure 9: Computer-Aided Design Capture of Compartment to Store Accelerometer Externally on Helmet

Lastly, the compartments each had a removable lid that will allow the team to access the components when needed. These lids can be seen in Figures 10 and 11.

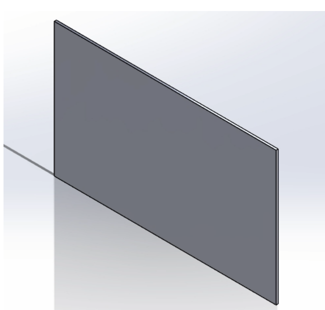

Figure 10: Computer-Aided Design Capture of Microcontroller and Battery Compartment Lid

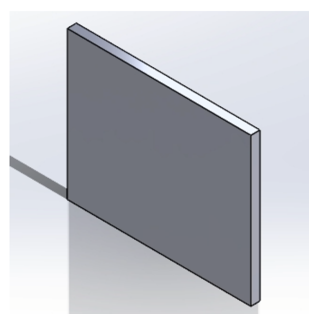

Figure 11: Computer-Aided Design Capture of Accelerometer Compartment Lid

Objective 3: Determining Risk of Head Injury

The risk of head injury was determined using Equation 1 which relies solely on the rotational acceleration of the head(Rowson et al., 2012).

$$risk \; = \; \frac{1}{1+e^{-(\alpha+\beta x)}} \qquad (1)$$

The resultant peak rotational acceleration is represented by the variable x and risk is a percent likelihood of receiving a head injury. The coefficients were determined to be: $\alpha \; = \; -\,12.531$ and $\beta \; = \; 0.0020 \, \frac{1}{rad/s^2}$ (Rowson et al., 2012). This equation can be seen in the graph that plots this function in Figure 12. The equation was found by estimating injury incidence rates for both concussive and subconcussive instances in collegiate athletes, creating a ratio between the two occurrences, and cross-referenced with data from other studies (Rowson et al., 2012). Rowson et al found alpha and beta regression coefficients by a generalized linear model technique. The curve in Figure 12, was also compared to NFL data recreated from the field done in a different study which resulted in a similar curve with the NFL's curve having lower rotational accelerations that cause a concussion. However, this was due to the NFL data looking only at concussion-causing accidents, while Rowson's data looked at all accidents that may or may not have caused a concussion (Rowson et al., 2012). From this equation, for the ease of system testing, a threshold was calculated so the team found the rotational acceleration that would result in a 20% risk. This and other thresholds were later implemented in the code of the Raspberry Pi. The resultant acceleration from the equation for a 20% risk of injury was calculated to be 5572.35 rad/s^2. The resultant peak acceleration from the equation for a 50% risk of injury is 6265.5 rad/s^2 and for a 75% risk of injury is 6814.81 rad/s^2. These thresholds were for Low Risk, Mid Risk, and High Risk, respectively.

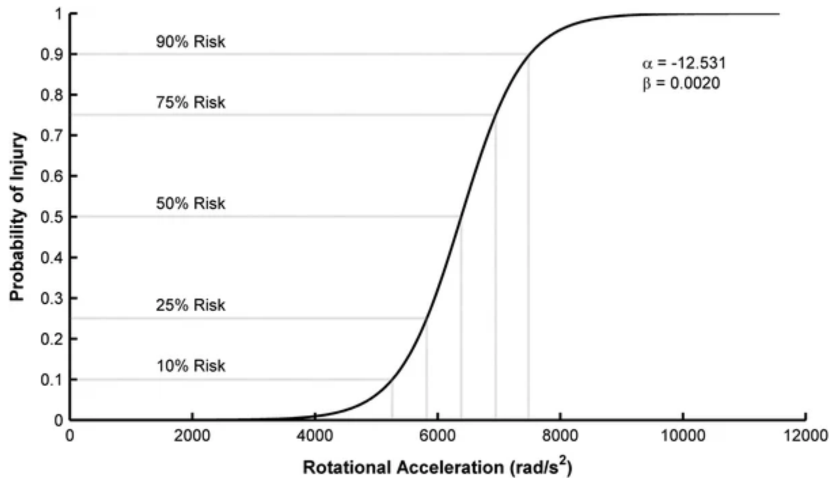

Figure 12: Effects of Rotational Acceleration on the Risk of Traumatic Brain Injury from Impacts Sustained by Football Players (Rowson et al., 2012)

Objective 4: Data Transmission

4.1 Data Flow

The data being collected from the sensor must be sent to a user interface such that the information is shown clearly to players, coaches, medical professionals, and anyone else involved in concussion diagnosis and treatment. The data is communicated wirelessly between an Arduino UNO directly on the helmet and a Raspberry Pi separate from the helmet. The process and components relevant to the process are depicted in Figure 13. The Arduino UNO connects the Raspberry Pi using the Bluetooth chip. The Raspberry Pi functions to receive, format, filter, and store the sensor data in 100 millisecond intervals. The code is consolidated into two shell scripts in two terminals after connecting to the Raspberry Pi.

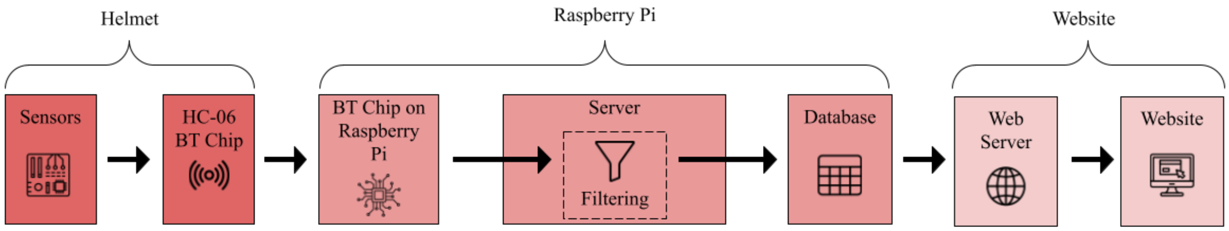

Figure 13: Flow Chart of Data Transmission from Smart Helmet Prototype to User Interface

Receive. The Raspberry Pi has a built-in Bluetooth sensor and an internet connection. In order to connect to the HC-06 Bluetooth chip, the Raspberry Pi must open and retain a connection. The Raspberry Pi also requires a function in order to read and decode the data being sent from the chip.

Format. After receiving the data, the Raspberry Pi formats the data before the server enters data into the SQLite database. This server is coded and runs on the Raspberry Pi and the data is locally stored on the Raspberry Pi. The data is received as integer values from the Arduino UNO that are separated by commas. They have been relabeled in the order: force sensor 1, force sensor 2, force sensor 3, force sensor 4, force sensor 5, x-acceleration, y-acceleration, z-acceleration.

Filter. In order to save space in the database, the data is only kept if the rotational acceleration poses a large enough risk to cause a concussion. Once the linear acceleration is sent from the Arduino UNO to the Raspberry Pi, the rotational acceleration is calculated with the equation:

$$rotational\ acceleration = \frac{\sqrt{(x\ sensor\ acceleration)^2 + (y\ sensor\ acceleration)^2}}{0.1458} \qquad (2)$$

The tangential acceleration is divided by 0.1458 m which is the radius of the head, found by taking the diameter of the football helmet and dividing it by half. This equation was found from the common equation:

$$tangential\ acceleration = r\alpha \qquad (3)$$

In Equation 3, tangential acceleration is the square root of $(x\ sensor\ acceleration)^2 + (y\ sensor\ acceleration)^2$, r is the radius of the head, and α is rotational acceleration. If the rotational acceleration is greater than the rotational value for a 20% risk determined in the objective above, it is sent to the database. Otherwise, the data is not saved into the local database. The filtering also classifies each data point of acceleration above 20% risk as low, medium, high risk for concussion.

Send. Once the data has been filtered and stored in the local database, a web server pulls it from the database to display on the website. This web server is linked to DronaHQ such that the information is sent through that platform's servers to display the number of impacts that passed the different thresholds on the template website with the respective data from each impact.

4.2 Website

The team used DronaHQ, an app development platform, to display the information collected and filtered from the smart helmet. The website displays the total count of all impacts that have over a 20% risk of causing injury in the top bar. It also displays the number of hits for the three separate categories: High Risk, Mid Risk, and Low Risk of causing a concussion, as seen in Figure 14. For each impact that falls into one of these categories, the date and time of the impact will be displayed as well as the peak force and acceleration from the impact. These numbers are imported through the DronaHQ servers by the web server from the local database stored on the Raspberry Pi. The web server connecting the database to the website runs when the program in Appendix B.4 is running on the Raspberry Pi.

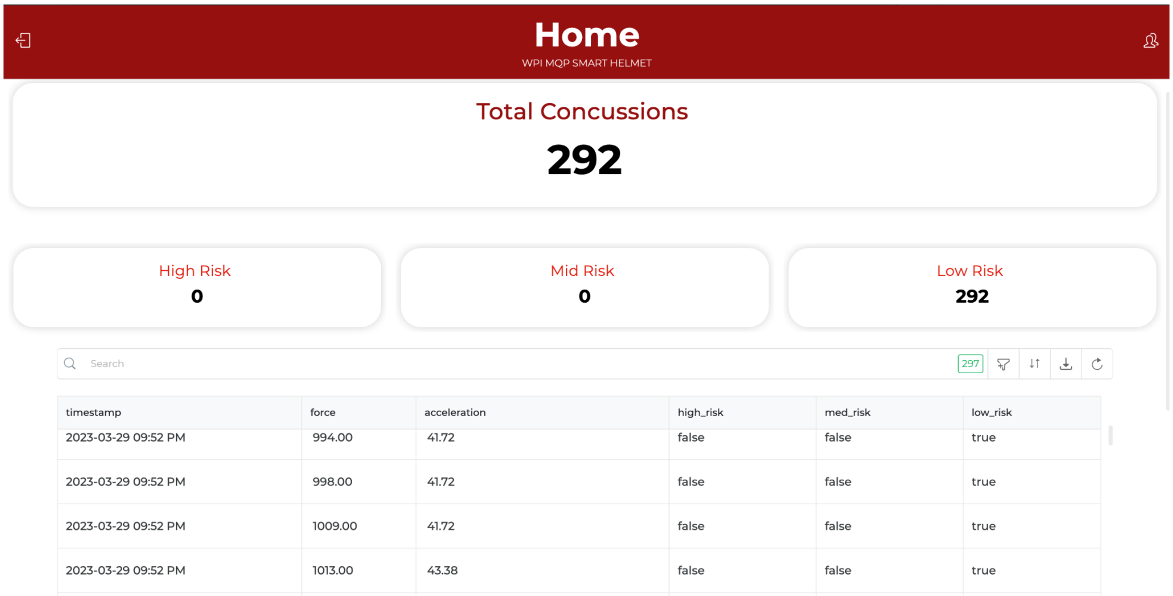

Figure 14: The Template Website from DronaHQ with the Total Number of Concussions, the Different Categories, and Data Displayed

Objective 5: Testing

5.1 Pneumatic Horizontal Linear Piston Testing Setup

The components used to complete testing on the helmet included a pneumatic piston, an air compressor, a podium for the prototype to rest on, and the prototype itself. The pneumatic piston was used to strike various locations to simulate an impact a football player would face on the field. These locations were the front, left, right, and crown of the helmet. An impact on the backside of the helmet could not be examined as this is where the electrical components are located. To control the force of the impact, the team used a valve on the air compressor to set outputs of 50, 75, and 100 psi. These pressures were used to simulate varying degrees of impact to the prototype. Lastly, the podium for the helmet had a hemispherical neck apparatus that allowed the helmet to account for the neck movement of a player after the head received an impact. The testing setup including all components is shown in Figure 15.

Figure 15: Smart Helmet Prototype Testing Setup and Components

5.2 Pneumatic Horizontal Linear Piston Testing Procedure

The testing procedure for the prototype, based on the article "American Football Helmet Effectiveness Against a Strain-Based Concussion Mechanism," occurred as follows (Ghazi et al., 2022). First, the helmet's electronic components were powered on and the helmet was placed on the podium's neck apparatus. Following this, the air compressor was set to the desired pressure output of either 50, 75, or 100 psi. Then, the team would open the valve from the compressor to the piston and the impact on the prototype would occur. Lastly, the team would find the impact in the data output and this data would be transferred into a spreadsheet for analysis. The prototype was tested at three impact forces in four locations. Each of the four locations received a total of nine impacts, three from each pressure, for a total of 36 impacts to the helmet. An image of an impact on the helmet can be seen in Figure 16.

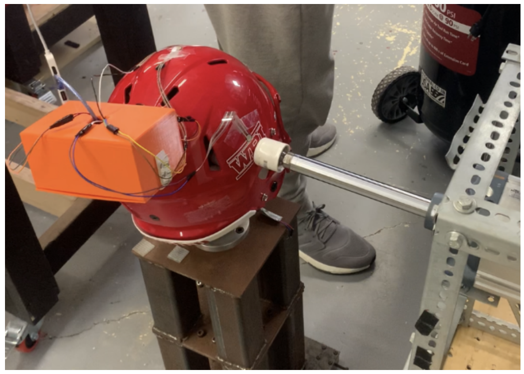

Figure 16: Example of Impact from Piston on Smart Helmet During Testing

5.3 Basis for Physical Testing Process

The procedure for the physical testing of the helmet was based upon the article "American Football Helmet Effectiveness Against a Strain-Based Concussion Mechanism," (Ghazi et al., 2022). This article discusses the relationship between helmet design and brain strain and includes a testing procedure that the authors used to develop their conclusions. This testing procedure consisted of a pendulum striking four different impact locations at varying speeds. The locations included the front of the helmet, the right side of the helmet, the front boss of the helmet, and the back of the helmet. The front boss of the helmet is the upper left-hand side slightly above the face mask. The speeds at which the helmet was impacted were 3.1, 4.9, and 6.4 m/s.

From this procedure, the team implemented the process of impacting four locations at three speeds for multiple trials. However, the team's general testing process varied from that of the published study in multiple ways.

First, the team used a pneumatic piston rather than a pendulum to deliver impacts to the helmet. This decision was made primarily due to the accessibility of the piston throughout the duration of the project. In order to use a pendulum, the team would have needed to build it and then ensure that it worked satisfactorily for testing. This was not feasible for the team and the piston was used instead.

Second, the team slightly changed the impact locations that the authors used in their procedure. Instead of impacting the back of the helmet as the fourth impact location, the top of the helmet was impacted in order to not destroy the compartments on the back. If the team had tried to hit the back of the helmet with the compartments attached, it likely would have broken off the PLA compartments and forced the prototype to be reconstructed. Also, instead of impacting the front boss of the helmet described, the team impacted the left-hand side of the helmet.

Lastly, the force at which the helmet was impacted was controlled by the valve for the pressure output of the air compressor rather than the velocity of the object attached to the pendulum. The three pressures used were 50, 75, and 100 psi, which were translated to 0.51, 0.86, and 1.03 m/s, respectively. To calculate these velocities, the team used motion capture to determine the total distance that the piston head traveled and the amount of time the head took to travel that distance.

Results

Final Helmet Assembly

The final assembly of the helmet, as seen in Figure 17, features two mounted PLA compartments that were designed using modeling software and then 3-D printed. The larger compartment was designed to hold the Arduino UNO, breadboard, Bluetooth chip, and battery. This compartment is mounted to the helmet through the use of a mount and threaded pin which slides through a feature on the back of the compartment, securely mating it to the helmet. The mount is fixed to the helmet by the use of Loctite super glue, which sturdily holds the mount in place. The mount also gives the compartment a range of motion to decrease the likelihood of the PLA feature breaking.

The smaller compartment located directly under the Arduino UNO compartment houses the accelerometer. This compartment is fixed to the helmet through the use of Command Strips which ensures that the compartment can only move in the same direction as the helmet. The accelerometer inside of the compartment is also fixed to the compartment using the Command Strips.

Force sensors were moved from the inside of the helmet to the outside. This needed to happen in order for the impacts to be measured. During testing, it was discovered that the helmet fit too snugly on the head apparatus and was not recording data from the impacts. It was instead measuring the force from the head on the padding and on the helmet itself. As a result, the sensors were moved to the outside to better measure the impact force.

Figure 17: Final Helmet Assembly

Final Connectivity

The connection between all the different components was established because the data is shown on the website. Data is collected from the accelerometer and force sensors by the Arduino UNO. That data is then sent wirelessly from the helmet to the Raspberry Pi through the connection of Bluetooth chips between the microcontroller and the miniature computer.

The website displays the number of total possible concussion-causing impacts as well as separates them into the three categories of High Risk, Mid Risk, and Low Risk. The data from this website is taken from a web server that is receiving the data from the database on the Raspberry Pi. Figure 18 shows successful connections between the database and the web server using a ping verification, and Figure 19 shows the connection between the web server and the website.

```
~/src/smartteam $ curl localhost:5000/ping
```

Figure 18: Connection Between Database and Web Server via Ping

Figure 19: Connection Between Web Server and the Website, DronaHQ

Computation of Rotational Acceleration

After completing physical testing and obtaining the raw data, the team used Excel to compute the angular accelerations from the coordinate data. The maximum angular acceleration from each impact was then taken and put into a table to determine the average acceleration for each location and velocity combination. From this data, it is clear that the angular accelerations increase alongside the increase in velocities despite a single outlier that skewed data for impacts on the right side of the helmet. This final data table can be seen in Table 3.

Table 3: Final Rotational Acceleration Data

Rotational Acceleration Data			
Velocity (m/s)	**0.51**	**0.86**	**1.03**
Front			
T1 Rot Accel (m/s^2)	62.11	144.20	139.89
T2 Rot Accel (m/s^2)	48.01	89.16	109.74
T3 Rot Accel (m/s^2)	56.56	82.59	144.68
Average (m/s^2)	**55.56**	**105.32**	**131.44**
SD	**7.10**	**33.83**	**18.94**
Left			
T1 Rot Accel (m/s^2)	126.10	82.30	200.32
T2 Rot Accel (m/s^2)	68.93	109.95	123.46
T3 Rot Accel (m/s^2)	63.23	161.43	104.69
Average (m/s^2)	**86.09**	**117.90**	**142.82**
SD	**34.77**	**40.16**	**50.67**
Top			
T1 Rot Accel (m/s^2)	111.65	54.87	246.91
T2 Rot Accel (m/s^2)	48.50	49.46	108.45
T3 Rot Accel (m/s^2)	55.30	219.59	109.95
Average (m/s^2)	**71.82**	**107.97**	**155.10**
SD	**34.67**	**96.70**	**79.51**
Right			
T1 Rot Accel (m/s^2)	118.00	165.18	306.73
T2 Rot Accel (m/s^2)	67.55	110.59	95.53
T3 Rot Accel (m/s^2)	79.99	190.20	111.65
Average (m/s^2)	**88.51**	**155.32**	**171.30**
SD	**26.28**	**40.71**	**117.56**

Discussion of Correlation Data

After completing data analysis of the physical testing of the helmet prototype, the team decided to compare the data collected to that of the procedure that the project's testing was based on. Using the data from the testing in "American Football Helmet Effectiveness Against a

Strain-Based Concussion Mechanism," (Ghazi et al., 2022), correlation coefficients were calculated by comparing two datasets using the CORREL function on Excel. Although the paper's procedure used higher velocity impacts on the helmet, the correlation data still presides with the theory that angular acceleration is the main factor in a concussion. The final data acquired from the article as well as the correlation data can be seen in Tables 4, 5, and 6.

Table 4: Comparison Data of Ghazi, K. et al

Data Summary of Ghazi, K. et al			
Velocity (m/s)	**3.1**	**4.9**	**6.4**
Side			
T1 Rot Accel (m/s^2)	1291.67	2624.13	3984.07
T2 Rot Accel (m/s^2)	1430.41	2813.72	4107.67
Average (m/s^2)	**1361.04**	**2718.93**	**4045.87**
SD	**98.10**	**134.06**	**87.40**
Front Boss			
T1 Rot Accel (m/s^2)	1353.90	2040.61	4499.30
T2 Rot Accel (m/s^2)	1361.43	2191.76	3996.86
Average (m/s^2)	**1357.67**	**2116.19**	**4248.08**
SD	**5.32**	**106.88**	**355.28**
Front			
T1 Rot Accel (m/s^2)	1477.49	2743.12	2945.64
T2 Rot Accel (m/s^2)	1459.20	2531.96	2846.45
Average (m/s^2)	**1468.35**	**2637.54**	**2896.05**
SD	**12.93**	**149.31**	**70.14**
Back			
T1 Rot Accel (m/s^2)	1886.11	2695.62	3372.58
T2 Rot Accel (m/s^2)	1847.62	2613.86	3106.65
Average (m/s^2)	**1866.87**	**2654.74**	**3239.62**
SD	**27.22**	**57.81**	**188.04**

Table 5: Average Angular Acceleration Correlations of Smart Helmet v. Ghazi, K. et al

Average Angular Acceleration Correlations Smart Helmet v. Ghazi, K. et al	
Side vs Right	0.9447
Side vs Left	0.9980
Front vs Front	0.9847

Table 6: Correlation between Piston Velocity and Rotational Acceleration

Correlation between Piston Velocity and Rotational Acceleration	
Location	Correlation
Front	0.9999
Left	0.9299
Top	0.9640
Right	0.9891

Discussion

The purpose of the helmet is to collect more information about hits to the heads of football players in order to make concussion protocols more thorough. By adding sensors to the helmet, the acceleration of the head can be digitally monitored to provide a medical professional with the calculated risk of concussion to the player. The updates occur through wireless data transmission to a website that displays the information. In practice, such a design would benefit football players that risk serious head injury each time they step on the field. Although the final product is only a prototype, it shows that the design is possible and would be useful in the field.

The helmet was tested to ensure that the system worked. The system components successfully worked together to send the data of the helmet in motion and being hit to be saved in a database and displayed on the website when the risk of a concussion, due to the rotational acceleration of the head, exceeded 20% according to the threshold found. The total number of hits that has at least a 20% probability of a concussion is shown at the top of the main page. It also displays the number of occurrences of high-risk, mid-risk, and low-risk data.

Additionally, the helmet underwent quantitative data testing and was compared to the study from Ghazi et al. for validation. The studies were set up the same way and used the same protocols. However, the forces exerted on the helmet in each study were different. Correlation values were calculated internally in the project as well as to data from the study that was repeated. The internal comparisons showed a high correlation. When comparing the velocity of the piston to the rotational acceleration from the accelerometer data, the correlation coefficient values were greater than 0.9 for the front, left, top, and right location data. Correlation coefficients range from -1 to 1 where negative values correspond to inverse relationships and positive values indicate a direct relationship. The values from the data were close to 1, indicating a strong correlation. This is expected because as the velocity of the hit increases, the magnitude of rotational acceleration should increase as well.

The correlation coefficients when compared to that from, "American Football Helmet Effectiveness Against a Strain-Based Concussion Mechanism," (Ghazi et al., 2022), also had high values. Only the comparison between the front boss acceleration values from the study and the right location from the smart helmet was lower than 0.9 with a value of 0.82. Although still high, the imperfect correlations are due to the differences in the exact locations of hits.

The team was not able to test the prototype with an impact forceful enough to reach any of the risks of injury thresholds but instead simulated smaller impacts with the equipment available. While an air-pressured piston was used, this setup did not have the ability to inflict an impact that would give readings higher than 5,800 rad/s, the rotational acceleration needed to surpass the 20% risk of injury minimum for database storage. The pressure limitation is due to the limitations of the equipment itself. An additional form of error was unidentifiable air leaks in the system. Fixing the leaks would not have allowed the team to reach the large rotational accelerations, so it was elected to save time and use the system available. The air pressure's real value actuating the piston was less than the pressure on the air tank.

Another limitation was with the Arduino UNO and the force sensors. While testing the helmet's accelerometers and force sensors with the force sensors mounted inside of the helmet, it was found that when one force sensor would be hit, the readings for all the force sensors would go off. When this occurred, the output readings started to spike and pulse dramatically, causing the readings to be unusable. This was thought to be caused by the limited processing power of the microcontroller, as a second accelerometer was also initially part of the circuitry but was unable to function as well. To try to fix this issue, the force sensors were placed on the outside of the helmet. With the limitation of time and budget, the team was unable to order a more powerful microcontroller or test different force sensors. The issue was averted by securing the force sensors on the external part of the helmet, although for future iterations it is ideal to have them inside the helmet as close to the head as possible for the most accurate readings.

Another issue encountered was the size of the compartment on the helmet needed to hold the circuitry, as the box encasing them is too large to feasibly add to a football helmet for actual use. While it is mounted to the helmet with a go-pro mount, so it does not snap off in motion; realistically, a player would not be able to play a game of football with the box on the back of their head. This version would not be able to be used in actual gameplay as the force sensors are on the outside of the football helmet, and repeated hits would eventually damage the sensors themselves.

Broader Impacts and Ethical Considerations

The first fundamental principle of the code of ethics for engineers is that engineers should use their knowledge and skill to enhance the welfare of humans (American Society of Mechanical Engineers, 2012). This smart helmet and the alert system would greatly assist in injury risk assessment as well as help assure no possible concussion-causing impact goes unnoticed, unassessed, or untreated. The high risk of CTE in professional football players is due to repeated impacts to the head, and these individual injuries cannot heal properly without rest and treatment. Giving medical staff sufficient information about the severity of an impact can help them more accurately and consistently determine the possibility of a concussion, adding some quantitative data to the diagnostic criteria rather than having to rely on qualitative and personal accounts. The other two fundamental principles of the code of ethics for engineers are that they strive to be honest, and impartial, and increase the competence of the profession (American Society of Mechanical Engineers, 2012). The team kept a very open line of communication throughout the entirety of the project, as well as with their advisors. They completed thorough research to help guide and back up important decisions made for the project. The first fundamental canon of the engineering code of ethics is that engineers shall hold paramount the safety, health, and welfare of the public in the performance of their professional duties, and this smart helmet was created specifically in the interest of decreasing the number of untreated concussions (American Society of Mechanical Engineers, 2012).

This smart helmet prototype was created for the purpose of decreasing the number of concussions that go undiagnosed and untreated in football. The big picture goal is to decrease the currently very high risk that football players have of developing CTE, the fatal brain disease. This would be done by assuring that players had a way of being alerted when they have endured a potential concussion-causing impact so that there can be immediate intervention to following concussion protocols and assess if there was any damage sustained from the impact.

This project involved the development of technology designed to be added onto a football helmet to turn it into a smart helmet. In the future, this could be developed into a mass-producible kit that athletes could purchase to set up with a helmet they already own. This would make concussion risk assessment technology more widely available to athletes and would allow more people to benefit from the use of this technology without needing to purchase a whole new helmet. Athletes who cannot afford to purchase a smart helmet could still benefit from the technology if they are able to buy a small add-on for the helmet they have. The creation and widespread use of a smart helmet add-on kit may also decrease the number of helmets that get replaced as well as decrease the number of helmets being purchased, indirectly contributing to a decrease in pollution.

With the continued and growing implementation of smart helmets in football, the advancement of this technology would help develop similar tools for other sports and activities, and eventually could be implemented into the daily lives of ordinary people. Devices like FitBits and Smart Scales are common household items that many now use to have specific knowledge about functions in their body they would not otherwise be able to consciously quantify, like heart rate and percentage of muscle over fat in the body. As smart helmets improve and become more easily mass-produced and cheaper, that technology could develop to be wearable outside of sports in a non-invasive and non-inhibiting way to have a constant record of the forces and changes in acceleration that the body is going through on a daily basis. This would decrease the number of injuries that go untreated because possible injuries would no longer go unnoticed or undetected.

1 in 20 people will experience a one-off epileptic seizure within their lifetime (Epilepsy Society, 2022). Although there is not much data on all people who experience a seizure, studies have shown that only 26% of epileptics are aware of all of their seizures, and 30% are never aware of any of their seizures at all (Blum et al., 1996). Seizures can cause serious injuries, from

bruises and burns to broken bones and, specifically, concussions (Sirven et al., 2013). Concussions caused by seizures that are not remembered will go untreated, and this could worsen the injury and be detrimental if more impacts are sustained. With the future development of smart wearable technology, people would be alerted to these injuries, intervene with treatment much sooner, and reduce the risk of additional and permanent damage.

The alert system that was developed during this project could be very useful in the future with the evolution of smart wearable devices. The elderly are another group that is vulnerable to injuries from falling, and with the alert system of this prototype, a family member can be alerted to any major fall their loved one may experience. Using these alerts in combination with future smart wearable devices could prevent people from being stuck alone in their own homes due to a fall or other injury by notifying another person, ensuring they are checked in on and receive the necessary medical care.

The National Operating Committee on Standards for Athletic Equipment (NOCSAE) is a non-profit standards development organization whose goal is to use data and research to improve athletic safety through the development of performance standards for athletic equipment.
The NOSCAE standards have been adopted by the National Federation of State High School Associations, the NFL, as well as the National Collegiate Athletic Association (Beam, 2022). Any state association playing under these organizations requires the football helmets worn by athletes to be tested and certified to meet NOSCAE standards through an independent third party, the Safety Equipment Institute (SEI). The helmet testing involves both a twin-wire impactor setup as well as a pneumatic ram impactor to accelerate and deliver impacts to a helmet and a headform inside. The headform the helmet is mounted on for the testing processes is a biologically-accurate variable-mass model instrumented with triaxial accelerometers at the

headform's center of mass. Helmets are tested with the twin-wire setup by being dropped to hit a rubber-padded steel anvil at specific velocities. The helmet is tested for impacts at seven different locations, three of which are random, with 29 impacts on each site. Four of the 29 impacts are purposefully lower velocities, and four more are done at high temperatures. The helmets are also tested with the pneumatic ram impactor using the same type of headform mounted onto a linear bearing table. These tests hit the helmet at six different impact locations, one of which is random, with the ram coming into contact with the sites at a speed of 19.6 meters per second (Oliver, 2021) .

A helmet must meet NOSCAE standards through every impact of the testing processes to be certified by the SEI. These standards set limitations on the peak severity indexes of the impacts, which correlate with the accelerations a headform endures and how long these accelerations last during the impact test. The standards also set limits on the peak rotational accelerations of the headform during the pneumatic ram impactor tests, and should not exceed 6000 rad/s during these tests (NOSCAE, 2019). The testing equipment used for this project does not have the capacity to reach the velocities used during NOSCAE, but if this project's prototype were to be developed further, it would need to be SEI certified before it could be a real contender in the football helmet market.

Recommendations

Following the completion of the major qualifying project, the team has successfully designed and tested a functional proof of concept for a smart wearable football helmet. With this working prototype, there are still plenty of avenues that could be taken down the road to further improve the smart helmet and project. The following sections will summarize the recommendations of the team for students who look to continue developing the smart wearable helmet in the future.

Electronic System Upgrades

The Arduino UNO microcontroller proved sufficient on many aspects of the design criteria. In future iterations of the project, a better microcontroller would make the project easier and the system more compact. Ideally, the team would have used a microprocessor that connects directly to the internet. This would allow for the removal of many components in the system, like the Bluetooth receiver and Raspberry Pi, and ultimately allow for direct communication of helmet data to a database and server. Due to the constraints of the WPI wifi, this was not possible and an Arduino UNO was used for its ability to be programmed with a Bluetooth module instead. One option would be to use the Raspberry Pi directly on the helmet. It has direct Internet access and operates with a 1.5 GHz quad-core processor as opposed to the 16 MHz processing power of the Arduino UNO.

The Arduino UNO was also not sufficient for some of the design aspects the team desired. Initially, the idea was to use more force sensors and at least two accelerometers to improve the accuracy of the data received during testing. This was not physically possible due to the amount of analog, digital, and serial pins the Arduino UNO had. There were also times that the Arduino UNO appeared to short circuit due to an influx of sensor input. For instance, during testing, there were often times the force sensors would pulse uncontrollably after impact, most likely due to the Arduino UNO being overworked. The team recommends using a more advanced microcontroller that can withstand more sensor input, as well as one that can connect directly to the internet. Ideally, two accelerometers on opposite sides of the helmet would be used. Additionally, the number of force sensors should be increased in future iterations, as the team initially had five but brought it down to four due to circuitry complications that could not be resolved. The force sensors should be put inside of the helmet as well, as the only reason they were externally placed on the helmet was due to the processing limitations of the microcontroller. The force sensors ideally should sense the forces impacting the skull and thus be placed inside the helmet where the padding would meet the head to be as close to the skull as possible.

The ESP32 microcontroller seems to be a viable option for future iterations of this project, as it has both wifi and Bluetooth capabilities, is coded in Arduino IDE, and has much stronger processing capabilities. Another option that could be researched is using radio communication to transmit data from the helmet to the desired device for notifications, as this method would be much less limited by distance than Bluetooth data transmission.

Consolidation of Parts and Compartment Design

Due to budget constraints, there were many smaller electronic components and designs that were not considered as these smaller components are very expensive. Should a team work on this project with an increased budget, it is recommended that an investment is made in smaller, more powerful components that can fit inside the helmet. These components would likely fit into compartments located in between the padding of the helmet and would remove all of the exterior compartments that were attached to the helmet that prevented testing of the back of the helmet and the potential use of the helmet in a practice or game scenario. One other recommendation that would improve the electronic design would be soldering the circuit in order to ensure that all components are securely connected. Soldering components onto a PCB protoboard would save space in the compartment and ensure the wires do not disconnect when being jostled around inside the helmet compartment. If the compartment remains external for future iterations, it should be designed specifically to fit the components into their own individual sections to minimize empty space and keep the compartment as small as possible to limit its interference while in play. It should also be designed to be more aerodynamic if it remains external to minimize interference with gameplay. The portable battery should also be switched out for a smaller power source to reduce the required space in the compartment.

Improve Testing Methods

After following the testing procedure from Objective 4 of the Methods section and analyzing the data collected, the team believes that there are new methods that can be put into place in order to further improve the quality of the data. These improvements will decrease the variability of the current procedure as well as remove some of the sources of error that were discovered during testing.

First, teams should consider using a spring-loaded piston in place of the pneumatic piston used in the current testing procedure. When testing with the pneumatic piston, there were air leaks that occurred between the hose and the fittings which increased the level of error between the psi output shown on the gauge versus the actual pressure that reached the piston. This source of error is removed by switching to a spring-loaded piston, which increases the number of known variables and does not have to consider the factor of air loss. If a spring-loaded piston is not an option, the use of a liquid thread locker on all junctions is recommended to significantly decrease the amount of air loss.

Also, the next team should seek an alternative to the hemispherical neck apparatus used in the current testing procedure. This current podium model, while it does allow the helmet to move in any direction through impact, does not mimic the exact motions and reactions of the human neck. The acceleration caused by the impact does not translate through the head of the dummy that was used for testing. This caused a variation between the data that was collected and the data that would be collected should a team use an apparatus that better simulates the movement of a human neck, which will be more accurate and relevant to the topic of head injury.

Another recommended method to test our football helmet is to have football players complete basic exercises while wearing the helmet to ensure that the sensors are not reading false positives. It is recommended to have them complete these exercises to check that the threshold is not being surpassed when they are doing basic movements such as running or throwing. This method is to make sure that the sensors can function normally.

Computer Science Major Assistance with Server/Website/App/Alerts

One of the biggest challenges with this project was data transmission. This seemingly small yet vital part of the project required full-time effort from two of the project members due to the lack of fundamental computer science knowledge in order to complete the coding side of the project. Frequent long meetings were held with computer science majors throughout the entirety of this project and were integral to its completion. These meetings were to discuss different options for completing the objectives, go over resources the team could use to follow through on these options, and troubleshoot issues with the code as well as edit, improve, and better understand it. Although a lot was learned and completed, other portions of the project were cut short due to resources being consumed in the research of the coding portion. With the addition of a computer science major the project could be developed much further much faster, considering the amount of time it took to get over the necessary learning curves. Having a computer science major would also allow the team to easily make small changes to the code to test the helmet on lower thresholds to then change the thresholds back to their original values for the helmet's realistic functions. There are thresholds currently set, but more adjustments to these thresholds would benefit from a cs major. The website could be further developed into a more accessible mobile application, could link player accounts to a coach, and could use a more direct alert system through the mobile devices for when a risk of injury is present. The website could be further developed aesthetically to more clearly show information, emphasize larger injury risk hits, and even display the general location on the helmet where an impact occurred if the force sensors are integrated enough to be used for that information. Other features to organize the history of impacts could be added as well, to allow players to easily search through their season's data on injury risks. Having a computer science major would also allow further customization of a website without using the website builder DronaHq. This website builder was only used as none of the students are CS majors and are not familiar with building a website. Although it functions well, it cannot be published without spending $10/per month. With a custom website, it could be done for free. Also with the freedom of customization, more visuals could be added like a diagram of the locations of the hits based on the force sensors. With a custom website, one could control the deployment, the hardware it runs on, and the performance, and avoid unauditable third-party code. Multiple methods of sending alerts were also researched, such as sending text messages through emails using a device's phone carrier or purchasing an API key to use a server for SMS messaging through Textbelt but these were not actualized.

Calculate the Risk Percent

The current program divides potentially concussive events into high, medium, and low risk based on resultant acceleration thresholds. Along with using predefined thresholds, future groups should use the resultant rotational acceleration and Equation 1 to calculate the precise risk of a concussion occurring. This would be possible by integrating Equation 1 into the code where the rotational acceleration is also calculated. The percent risk for each impact should then also be displayed on the website.

Consolidate Data Transmission

The way data is transmitted from the helmet to the user interface should be consolidated for future iterations of this project. The code successfully sends data where it needs to go but moves it in an inefficient manner. The code should be consolidated to use a single server and database rather than multiple.

One issue the team overcame was a change in the Raspberry Pi's IP address. It remained consistent for months and then changed unexpectedly. This was overcome by connecting the Raspberry Pi to a monitor and grabbing the new IP address. In the future, the Raspberry Pi should be given a static IP address or host name so it will not require changing the code.

It would be beneficial to create a new website from scratch using software such as HTML, CSS, & JavaScript. This would give the next team more control over the website and a more comprehensive user interface. Due to a lack of time, the website was not a priority for the team. However, there was an initial website mapping done that would be helpful for future website iterations. This can be seen in Appendix C and should be adapted by future project teams. This project has the data moving from the helmet microcontroller to the Raspberry Pi, stored in a database with a local server on the Raspberry Pi, pulled from the database, and put onto a separate web server, which is then communicated through DronaHQ's servers to display on the website template through their platform. By having a single device on the helmet that can connect to the internet and send this data to a user interface, future iterations should eliminate the need for multiple servers and instead have a single web server that can combine all necessary functions.

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APPENDIX A: Code

A.1: GitHub Link

Below is the link to the GitHub containing all the code relevant to the project, running on the Raspberry Pi or Arduino UNO.

https://github.com/rkrizan01/smartteam

A.2: Arduino UNO Code

The code below is runs on the Arduino UNO to collect the data from the sensors and send it in the correct format to the Raspberry Pi.

```
#include <SoftwareSerial.h>

#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_ADXL375.h>

SoftwareSerial BTserial(2, 3); // RX | TX


#define ADXL375_SCK 13
#define ADXL375_MISO 12
#define ADXL375_MOSI 11
#define ADXL375_CS 10



#define FORCE_SENSOR1_PIN0 A0 // FSensor 1
#define FORCE_SENSOR2_PIN1 A1 // FSensor 2
#define FORCE_SENSOR3_PIN2 A2 // FSensor 3
#define FORCE_SENSOR4_PIN3 A3 // FSensor 4
#define FORCE_SENSOR5_PIN4 A5 // FSensor 5


Adafruit_ADXL375 accel = Adafruit_ADXL375(12345);
```

```
void setup() {

Serial.begin(9600);
BTserial.begin(9600);

while (!Serial);
  Serial.println("ADXL375 Accelerometer Test"); Serial.println("");


  if(!accel.begin())
  {

    Serial.println("Ooops, no ADXL375 detected ... Check your wiring!");
    while(1);
  }
    // Range: +-200g
}
void loop() {

  sensors_event_t event;
  accel.getEvent(&event);

int sensorValueX = event.acceleration.x;
int sensorValueY = event.acceleration.y;
int sensorValueZ = event.acceleration.z;


int sensorValue1 = analogRead(FORCE_SENSOR1_PIN0);
int sensorValue2 = analogRead(FORCE_SENSOR2_PIN1);
int sensorValue3 = analogRead(FORCE_SENSOR3_PIN2);
int sensorValue4 = analogRead(FORCE_SENSOR4_PIN3);
int sensorValue5 = analogRead(FORCE_SENSOR5_PIN4);

//IMPORTANT: String has to be in Form: 1234,1234,1234,1234;
//every Value has to be separated through (',') and the message has to
//end with a semicolon (';'))
```

```
BTserial.print(sensorValue1);
BTserial.print(",");
BTserial.print(sensorValue2);
BTserial.print(",");
BTserial.print(sensorValue3);
BTserial.print(",");
BTserial.print(sensorValue4);
BTserial.print(",");

BTserial.print(sensorValueX);
BTserial.print(",");
BTserial.print(sensorValueY);
BTserial.print(",");
BTserial.print(sensorValueZ);
BTserial.print(";");

delay(100);
}
```

APPENDIX B: Website User Interface Mapping