Smart Wearables Devices: An IoT-Enabled Bicycle Helmet for Recreational and Mountain Cyclists

A Major Qualifying Project
submitted to the Faculty of
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Abstract

Despite increasing calls to improve athletic safety technology athletics, only the most popular sports (e.g. American football) have seen significant progress. This project implements Internet-of-Things (IoT) devices on a bicycle helmet to collect critical data for assessing sustained head trauma. We employed a three-axis accelerometer as well as force-sensitive resistors on an off-the-shelf Bontrager Rally WaveCel helmet to determine the G-force of impacts and pinpoint its location. Our findings emphasize the pressing need for additional research in the athletic safety technology industry with respect to cycling.

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Recommendations	Amber, Nichole	Ruchita
Conclusion	Brendan	Brendan

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1. Introduction and Background

The popularity of cycling as exercise extends from children biking together in a neighborhood to skilled athletes completing a six-hour mountain biking challenge. Despite the vast interest in cycling for both recreation and exercise, limited developments have been made to decrease the number of injuries sustained from cycling. In the United States, cycling is the second most frequent sports and recreation activity leading to childhood visits to the emergency department (ED) (Embree et al. 2016). Recreational biking injuries occur primarily in children from 5-14 years, while mountain biking injuries peak in people from 20-39 years old (Thompson 2001). Concussions are among the most common cycling injuries, resulting in adverse side effects ranging from temporary nausea and headaches to permanent brain damage. Considering the vast interest in bicycling amongst all age groups, helmet designers must implement better safety measures and equipment for the sport.

Despite concussions being the most common injury in cycling and other sports, only the sports of football and hockey have substantially invested in forms of injury prevention and recovery equipment. By comparison, protective cycling equipment has seen minimal changes since its inception, and any such advancements have been solely mechanical. Our Smart Helmet aims to combine physical protective upgrades with smart sensor technologies that analyze the forces exerted on the helmet after an impact. These modifications will improve bikers' safety, offering additional physical protection and allowing riders to quickly assess a collision's severity. The overall goal of the smart helmet is to mitigate the risk of concussions and other head-related injuries.

1.1 Overview

Within the sports community, smart wearable devices that can track injury, especially smart helmets, are rising. Examples of these helmets are seen in football, baseball, and other sports with helmets (Seshadri et al.). However, bicycling, an activity that heavily relies on helmets for safety, lacks well-made smart helmets. Many mechanically well-designed helmets exist in cycling, such as Multi-directional Impact Protection Systems, or MIPS, designed to rotate with the wearer to avoid rotational injuries (Mulcahy). However, no smart sensor-rich helmets exist, and sensor-rich cycling helmets are not a prominent topic of conversation. Another significant gap in helmet technology development is improved helmets for non-competition athletes. Research shows that smart helmets in sports are generally aimed toward professional sports players (Seshadri et al.), leaving the casual audience without important safety mechanisms. This audience is more at risk due to a lack of professional athletic trainers ready to tell them whether or not they have a head injury and how to heal best. This team's product aims to fill that gap in modern technology and allow riders safer participation in the sport they love.

A significant consideration for this project was determining which of the many bike helmets best suited our purposes. Helmet types change based on activity, with different helmets for recreational street biking, competitive street biking, mountain biking, and acrobatics, and are further differentiated by a targeted age range. Usually, the difference between age groups in bike helmets is merely size, but the difference in recreational and mountain biking helmets is drastic. Mountain bike helmets tend to be heavier and offer more protection by covering more of the head, including the chin and upper neck area. Meanwhile, recreational and competitive street cycling helmets are thinner and lighter, covering the top and sides of the head. To incorporate safety features for both types of cycling, the Smart Helmet uses the market-developed Bontrager

Rally WaveCel as a base, which combines the two helmet designs (SmartEtailing). This helpful feature allows the team to consider the advantages and restraints of both types of helmets for our Smart Helmet design purposes.

1.2 The Rise in Cycling Injuries

As biking becomes an ever more popular form of exercise, injuries occurring due to cycling have also been on the rise. Dr. Gloria C. Cohen, a sports specialist who served as the coordinating physician for the Canadian cycling team, observed some of the most common injuries associated with biking. During her time in practice, she has treated cycling injuries related to seats, handlebars, and catastrophic collisions. While seat-based and handlebar-based injuries can be severe, they are easily preventable (Cohen 631). Seat injuries often start with saddle soreness from sitting on the bicycle seat for long periods but can be mitigated with a proper saddle or ointments. Wrist injuries caused by applying pressure to nerves in the wrist on the handlebars are preventable using padded handles or gloves. But the most concerning injuries are those caused by collisions, which are less easily prevented based on existing cycling equipment.

Mountain biking, in particular, is observing a rising number of exactly these concerning injuries, including severe cranial injuries caused by falling forward. According to PubMed contributors Kylee B. Aleman and Michael C. Meyers, this increase can be primarily attributed to a much younger demographic participating in the sport. They emphasize that this increase in injuries may only be the “tip of the iceberg” due to unreported injuries (Aleman, Meyers 80). Dr. Cohen further observes that teenagers and young adults are most likely to sustain injuries when attempting “too much too soon,” indicating a need for better injury prevention among the younger demographic. (Cohen 628).

Tania Embree et al., contributing authors to the Journal of the American Academy of Pediatrics, further explore the individual and environmental factors contributing to adolescent bicycle injuries. Up to 8% of deaths and 15% of injuries in this demographic come from traffic-related incidents when children are recreationally cycling. Embree et al. conclude that the youth bicycling environment needs better accident prevention measures. Aleman and Meyers echo this sentiment in their article and outline several practical accident prevention methods. These include instituting a minimum age for children to ride bicycles on roadways trafficked by other vehicles, educating riders about how common injuries occur, and how proper equipment such as helmets and gloves can go a long way to avoid or mitigate catastrophic injuries (Aleman and Meyers 87).

The previous studies agree that the most damaging and most problematic injuries in cycling occur during collisions. Repercussions range from minor abrasions to severe concussions and fatal head injuries. Aleman and Meyers estimate approximately 85% of fatalities in biking are from collisions (Aleman and Meyers 80). Because these injuries mitigate potential brain damage, helmet initiatives have been more effective than safe-bicycle practice education and are a focal point of most prevention programs (Embree et al.).

Dr. Cohen asserts that using an approved helmet is crucial in preventing fatal head injuries (Cohen 632). However, Dr. Cohen also observes an increase in the popularity of soft-shell expanded polystyrene (“EPS”) helmets made of polystyrene foam, commonly known as styrofoam. These helmets are low in cost and are much lighter than approved hard-shell types. However, EPS helmets can be easily penetrated by objects and exhibit design flaws that frequently contribute to head and neck rotational injuries. The previous issues indicate EPS helmets are largely ineffective as a protective measure (Cohen 632).

Further emphasizing the importance of approved helmets is a 1990 article from Health News, which focuses on children under 15. Specifically in Quebec and Ontario, 14 percent of childhood trauma deaths are associated with bicycle accidents culminating in approximately 50 deaths every year (“Health News”). Bicycle accidents are the number one cause of head injury hospital admissions among children under 15. And, 90 percent of these injuries occur while unsupervised children are biking with their friends not very far from home (“Health News”). The article also highlights the risks of injury in unhelmeted versus helmeted bikers, observing that 45 percent of unhelmeted cyclists experienced brain injuries compared to six percent in those who wore effective helmets (“Health News”).

1.3 The Contemporary Market

1.3.1 Mechanical Advancements of Helmets

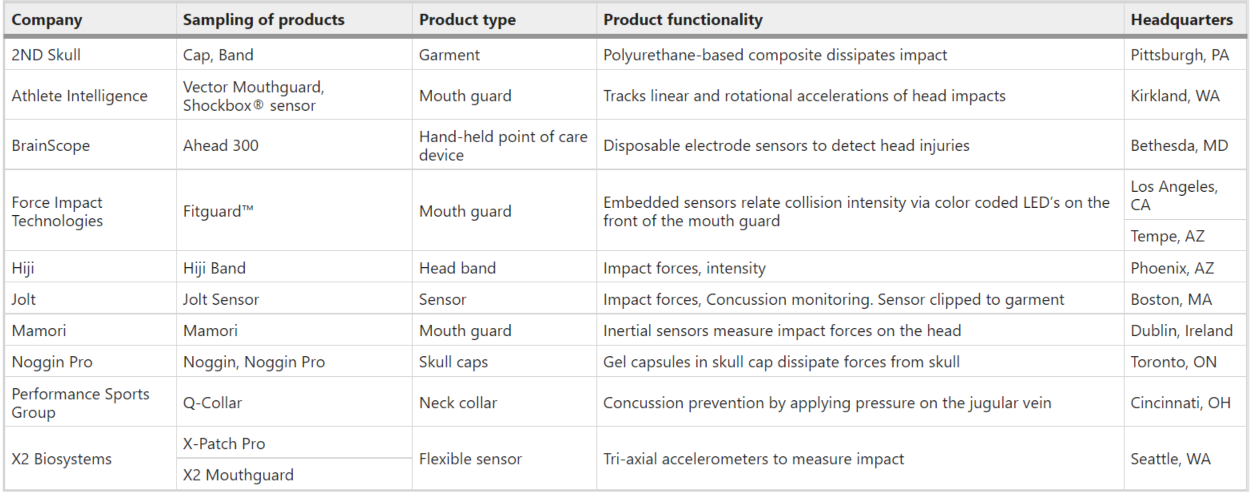
As cycling has become more popular, bicycle helmet construction has seen some mechanical improvement. Multi-directional impact protection system (MIPS) helmets help reduce the rotational forces absorbed by the head using slip-plane technologies (Mulcahy). Although more expensive than EPS helmets, MIPS helmets provide more safety, as they include advanced methods for head protection. MIPS helmets are specifically designed to reduce injuries caused when the helmet slides. MIPS helmets use a two-shell helmet system to avoid sliding friction injuries -- the solid outer shell takes the brunt of the impact from the fall, and the inside surface adjusts to head and body movement to protect against dangerous whiplash (Mulcahy).

Another new commonly used helmet is the WaveCel helmet. WaveCel helmets consist of a cellular copolymer material made up of multiple layers to help absorb more force, both linear and rotational. These materials are essentially a form of cellular plastic produced by introducing varying gas levels to the plastic polymer, allowing manufacturers to create a range of densities from that of a solid board to a more giving cellular foam (Berins 541). The cellular copolymer material in a WaveCel helmet is made to “flex, crumple, and glide, absorbing rotational energy” (Loria). While MIPS helmets are a vast improvement over EPS helmets, WaveCel polymer construction provides the ultimate cycling helmet protection for the brain. Consequently, WaveCel helmets are the most expensive, top-of-the-line option for both recreational and competitive cyclists (“WaveCel”).

EPS, MIPS, and WaveCel helmets were compared using oblique impact testing to analyze their effectiveness (Bliven et al.). During testing, Bliven et al. vertically dropped the helmets at the same speed (4.8 m/s) onto an angled anvil. The anvil was set at three different angles during the experiment -- 30°, 45°, and 60°. One additional test was performed at a speed of 6.2 m/s at a 45° anvil angle (Bliven et al.). Specialists conducted all four test setups five times per type/helmet brand. The results show that EPS helmets effectively prevent fractures to the skull but are ineffective at preventing concussions due to a lack of rotational force reduction (Bliven et al.). In this situation, rotational force (mainly on the neck and head) is the main culprit behind most concussion injuries (Cohen 6XX). Both MIPS and WaveCel helmets are significantly more effective in reducing these rotational forces. However, the “differences in efficacy between the [helmets]” as well as test result gaps in the effectiveness of the MIPS and WaveCel helmets demonstrate the pressing need for more advanced helmet technologies (Bliven et al.).

1.3.2 Electronic Advancements in Sporting Safety Equipment

With technological advancements in multi-sport equipment multiplying, it is possible to augment the effectiveness of bicycle helmets with smart wearable sensors that monitor an individual's health to reduce injury risk (Seshadri et al.). The majority of sensors used in impact sports include accelerometers, global positioning satellites (GPS), impact sensors, and inertial measurement units (IMU) (Seshadri et al.). These sensors allow athletes and medical personnel to accurately track movements and understand the levels of impact for necessary proactive treatment. In other words, while cyclists can not always avoid injury, sensors detect injury levels and provide participants with real-time information to encourage them to seek the necessary medical treatment (Seshadri et al.). However, recreational cyclists or mountain bikers do not use many available impact-absorbing sensor devices, including mouthguards, headbands, and skull caps (So). Figure 1 below provides current examples of smart wearable sensors that detect impacts.



Company	Sampling of products	Product type	Product functionality	Headquarters
2ND Skull	Cap, Band	Garment	Polyurethane-based composite dissipates impact	Pittsburgh, PA
Athlete Intelligence	Vector Mouthguard, Shockbox® sensor	Mouth guard	Tracks linear and rotational accelerations of head impacts	Kirkland, WA
BrainScope	Ahead 300	Hand-held point of care device	Disposable electrode sensors to detect head injuries	Bethesda, MD
Force Impact Technologies	Fitguard™	Mouth guard	Embedded sensors relate collision intensity via color coded LED's on the front of the mouth guard	Los Angeles, CA Tempe, AZ
Hiji	Hiji Band	Head band	Impact forces, intensity	Phoenix, AZ
Jolt	Jolt Sensor	Sensor	Impact forces, Concussion monitoring. Sensor clipped to garment	Boston, MA
Mamori	Mamori	Mouth guard	Inertial sensors measure impact forces on the head	Dublin, Ireland
Noggin Pro	Noggin, Noggin Pro	Skull caps	Gel capsules in skull cap dissipate forces from skull	Toronto, ON
Performance Sports Group	Q-Collar	Neck collar	Concussion prevention by applying pressure on the jugular vein	Cincinnati, OH
X2 Biosystems	X-Patch Pro X2 Mouthguard	Flexible sensor	Tri-axial accelerometers to measure impact	Seattle, WA

Figure 1. *Impact detecting smart wearable devices.*

Although several impact devices are available, there is still a clinical concern about the lack of specialized sensors that can accurately detect and analyze impact forces on the head to decrease the severity of concussions through proactive treatment (Seshadri et al.). Companies including Athlete Intelligence, Force Impact Technologies, and Mamori have developed mouth guards embedded with sensors to detect concussions (Seshadri et al.). However, mouth guards are not used by a full range of sporting participants and are almost absent among bicyclers. The National Football League (NFL) adopted the X-Patch pro wearable by X2Biosystems, an adhesive epidermal sensor worn behind the ear to detect concussions accurately (Seshadri et al.). The sensor technologies, as mentioned above, continue to improve athlete safety. However, these improvements have not been marketed explicitly within the cycling community, which is not considered violent as other impact sports.

One of the few advancements made to promote safety specifically in the cycling community is ICEDOT, a smart crash sensor mounted to the back of bicycle helmets. By pairing the sensor to a smartphone using the ICEDOT mobile app, the sensor detects cyclist movement, changes in forces, and sudden impacts (“ICEdot | ICEdot Crash Sensor”). The device will set off an alarm after a severe blow, allowing the cyclist to evaluate their injury and simultaneously notify emergency contacts if the alarm is not disabled. The ICEDOT sensor is modular and can be applied to other sporting equipment, including skateboarding or skiing helmets (“ICEdot | ICEdot Crash Sensor”).

Another bicycle helmet innovation is the “Multifunctional Bicycle Helmet.” It uses Internet-of-Things (IoT) technologies and functions to improve rider convenience and safety. The Multifunctional Bicycle Helmet includes technology that allows riders to safely and hands-free announce their presence and intended direction (Tsai et al.). It offers an embedded turn signal that can indicate direction with the tilt of a head, LED light strips automatically activated at dusk, cyclist GPS positioning, and sensors that detect approaching vehicles (Tsai et al.). The MBH offers an impressive array of safety features but has yet to reach the market (Tsai et al.). It is also absent from the injury detection features found in other safety equipment.

1.4 The Knowledge Gap

As more individuals take on the sport of cycling, the need for better safety equipment is evidenced by a commensurate rise in cycling accidents. Moreover, adolescents under the age of 15 are beginning to participate in the more rigorous cycling pursuits usually dominated by adults, including mountain biking. Younger participants are less prepared or inclined to maintain safety protocols despite the additional danger, and cyclists of all ages are limited by safety equipment that is not best designed for the sport.

While some helmets offer safety features, other sports offer equipment with advanced sensors that help identify injury levels to promote timely and accurate medical assistance. This technology *is* beginning to make its way into bicycle helmets. Still, there remains a gap in using these potential life-saving sensors between participants in contact sports and cyclists. The cycling market is ready for helmets equipped with sensors that provide the rider with the necessary medical information to indicate a concussion and prevent it from becoming catastrophic or fatal.

2. Methodology

The Smart Helmet is intended to aid mountain and recreational bikers in assessing impact-related head injuries in real-time. Our device offers quantifiable data from collisions that allow the user to self-diagnose injuries using the information gathered from the helmet's technology. Our team incorporated these functions into our design by addressing three objectives, which focus on design, simulation, and testing. These objectives include:

1. To accurately design an ergonomic, comfortable, and user-friendly integration of sensor technology in a standard mountain biking helmet.
2. To simulate potential biking accident conditions through Ansys LS-Dyna software and compare them to real-time data gathered and processed via a mobile application.
3. To test helmet technology integration and verify the functionality of the sensors.

Before starting the designing and testing phases, we first identified which features were necessary for the Smart Helmet to function. The design parameters we determined emphasized how critical the user-friendly aspect of the helmet was, both in its everyday use and in reading the gathered data. The design functions are broken into mechanical and electrical processes, seen in the lists below.

I. Mechanical:

1. Lightweight, slim, and still be able to provide standard protection
2. Have an easy to remove/reattach battery for simple recharging and reconnection to the helmet
3. Sensor placement should not affect user experience
4. Place the sensors in areas where accurate readings can be measured

II. Electrical:

1. Program sensors to continuously transmit information to the application software
2. Ensure that the sensor wiring is safe from outside conditions
3. Communicate the severity of impact, falls, collisions, and other accidents to the user

The primary constraint in this design is the size and positioning of sensors. We worked with an off-the-shelf helmet, the Bontrager Rally WaveCel, limiting the available placement space for the sensors. During the design process, we carefully considered the selection of mechanical and electrical materials and appropriate wiring design and sensor placement.

2.1 The Design Process

2.1.1 Mechanical

To create a viable model of our proposed helmet, we created Computer-Aided Design (CAD) models of the helmet, including microcontroller, accelerometer, shield, and pressure sensors. The team gathered information from various distributors about helmet components to create accurate CAD models based on listed materials and dimensions. This allowed the team to run simulations on the CAD models while waiting for the components to ship. Once the components arrived, the models were checked for accuracy based on the actual helmets. The CAD models were created in separate files by different Mechanical Engineering team members and then combined into one final helmet file. The images below show each component separately, and the final image has all the components attached to the helmet.

Figure 2. *CAD Model of the Helmet Base.*

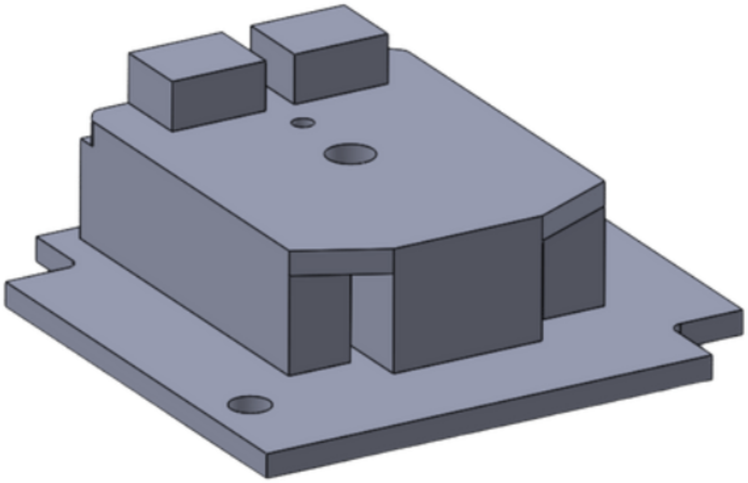


Figure 3. *CAD Model of Example Component.*

Once the components were complete we were able to run them through simulation software. This is done to recreate real-time forces and see how the helmet will act under loads at certain angles or pressures. Our team also wanted to use the simulations to see where it would make the most sense to apply the pressure sensors. We set the back base of the helmet as the fixture, and applied forces along various panels along the helmet to test the displacement that occurred under the force. Finally we applied the correct type of material to the helmet to yield accurate values. We tested our helmet with different pressures and different forces. Pressures were used in testing because it creates an even distribution of the applied force. Meanwhile, different direct forces were used as well as pressure in testing because the direct force simulated the events of a real-life crash. . Below we have included some images from the simulations. Overall we found that the front to middle of the helmet had the most possible deflection zones, so we will make sure to include pressure sensors along those areas.

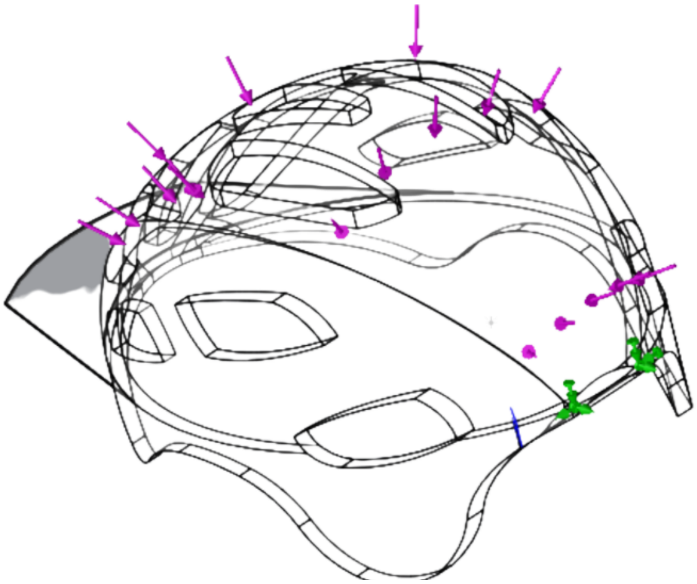


Figure 4. *Simulation Model of Helmet.*

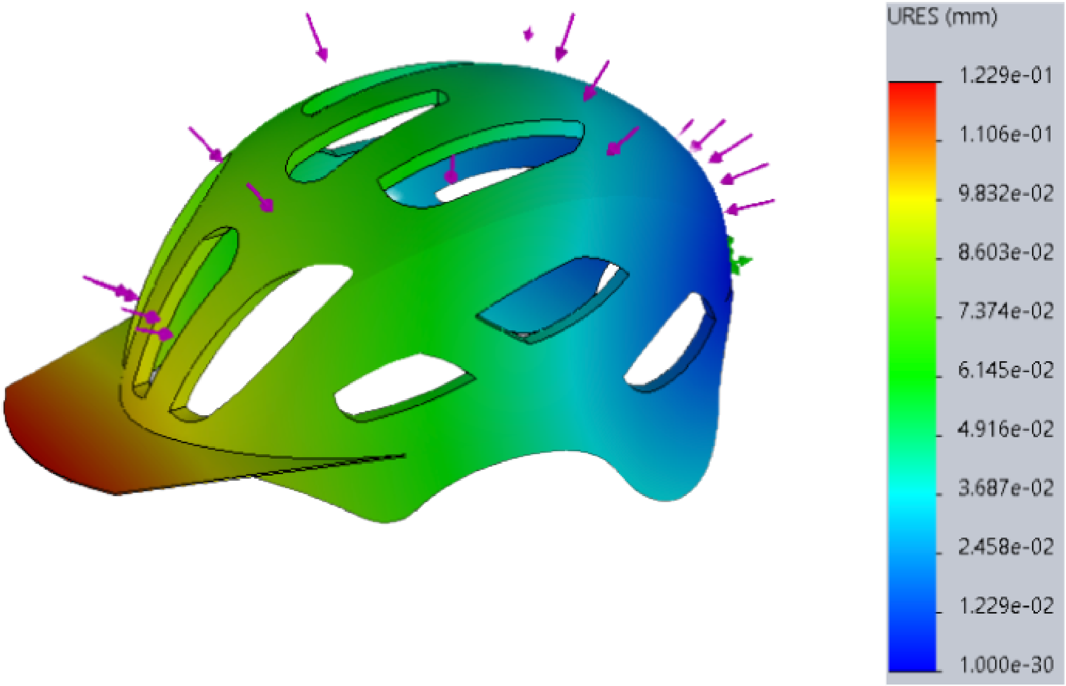


Figure 5. *Simulation Model With Stress Values.*

In order to integrate the sensors and accelerometer with the bicycle helmet, the mechanical engineering team designed an electronics housing using SolidWords. To create a housing that was easily accessible, we designed a gopro mount, a common action camera used by many cyclists. The mount would allow users to detach and reattach the housing if necessary. The final housing took many iterations, with the first solidworks design shown in the figure below.

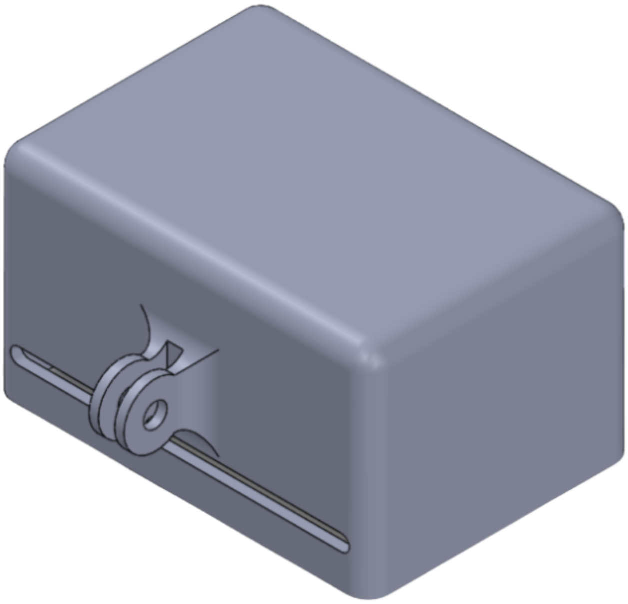


Figure 6. *First CAD Design of Housing Unit.*

The slot in the box was created so the wires from the pressure sensor could run through the box and into the helmet. The housing protects the wires from the weather and prevents any electrical problems. Once the housing was designed in solidworks, we transformed the CAD files into stl files so we could use the 3d prints to get a physical housing model, shown in the figure below.

Figure 7. *First Housing Unit Design.*

After successfully mounting our model to the helmet and wiring all the electronics in the housing, we determined the battery should also be mounted to the housing to create the most ergonomic design. Our final model includes a slot for the battery to slide into and be secured by velcro straps and power the electronics. A small hole at the bottom of the housing allows the battery cable to plug in the electronics through the housing. The figure below shows the final completed design of the housing in solidworks.

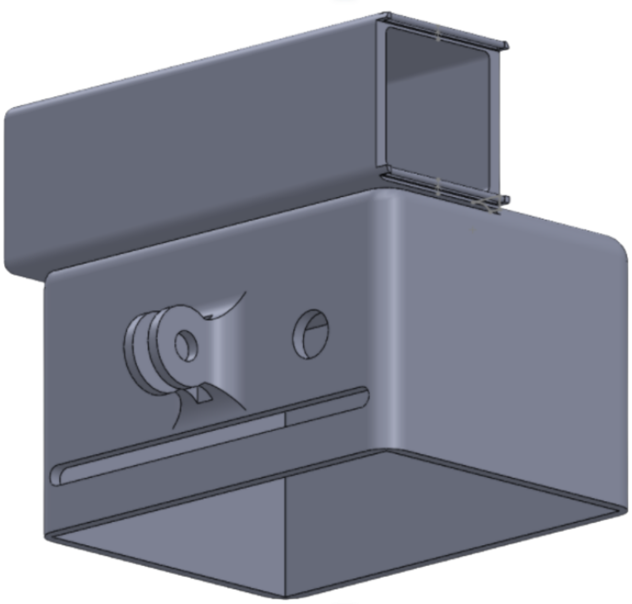


Figure 8. *Second CAD Design of Housing Unit.*

Once the housing was printed, we assembled the electronics and attached the housing to the helmet. The electronics fit into the housing and the pressure sensors were wired through the housing and into the helmet to detect the location of impacts.

Figure 9. *Second Housing Unit Design.*

2.1.2 Electronic

The microcontroller was identified as the most crucial component to allow proper helmet function. This microcontroller served as a gathering hub for all our sensor data and was used for packaging and transmitting the information to a central application. To complete this function, it was necessary for our microcontroller to connect wirelessly to a phone to enable data transmission. The team determined two main ways to complete the transmission: via Wi-Fi or Bluetooth. Deciding on the appropriate physical size of the microcontroller was another important consideration. Mounting a large controller on the helmet would have rendered it unstable, ultimately reducing the reliability of our product. Finally, the microcontroller required the appropriate number of input/output pins to mount sensors and transmit data.

We settled on a small, Wi-Fi-based microcontroller. The Particle Photon shown in the figure below met all the necessary criteria for our functioning microcontroller. With built-in Wi-Fi capabilities and a companion app to aid programming, the Particle Photon could handle our project's essential functions. Furthermore, it offered 14 usable input/output pins to hold necessary sensors and potential attachments.

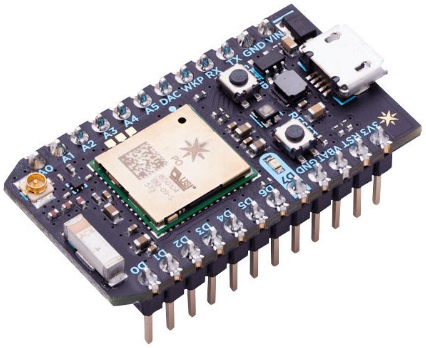


Figure 10. *Particle Photon Microcontroller*

https://www.newark.com/particle/phntrayh/dev-kit-wireless-connectivity/dp/62AC5483

However, the Particle Photon did not possess any sensor capabilities of its own. To gather our desired data, we needed to connect external sensors to the microcontroller and program it to receive information continuously. The two necessary sensors for this project were position sensors and an accelerometer. We programmed the position sensors to locate where an impact occurred. The accelerometer was arguably more vital, as it measured any rapid acceleration or deceleration in G-force that could potentially result in a concussion from whiplash movements.

The team required an element capable of measuring large amounts of force in a compact package. Initially, our team planned to place several circular force sensors inside the helmet as nodes, using each individual sensor to give an approximate impact location. We considered this idea to be of merit, but in application, it was not as locationally accurate as we initially hoped. We then stumbled on a force-position sensor, which relayed to the microcontroller a precise position while it pinpointed the amount of applied force. The force-position sensor is shown below.

Figure 11. *Force-position Sensor*

The team set three goals to determine the most compatible accelerometer for our Smart Helmet. Most importantly, it needed to measure enough acceleration to detect a potential concussion. Secondly, it needed to work well with the Particle Photon microcontroller for programming purposes. Finally, it needed to be compact enough to physically fit alongside the microcontroller on the helmet itself. To satisfy these conditions, we settled on a Particle Photon accelerometer attachment. While the base attachment did not initially possess the required range, we could special order the appropriate size and begin code work on the original in advance of its arrival.

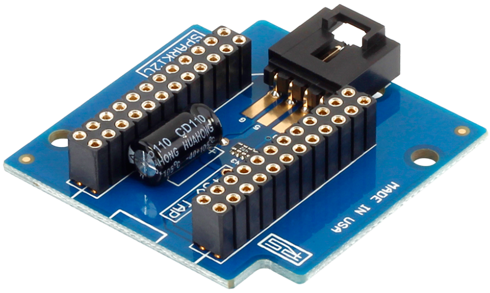


Figure 12. *Particle Photon I2C Shield*

https://store.ncd.io/product/i2c-shield-for-particle-photon/

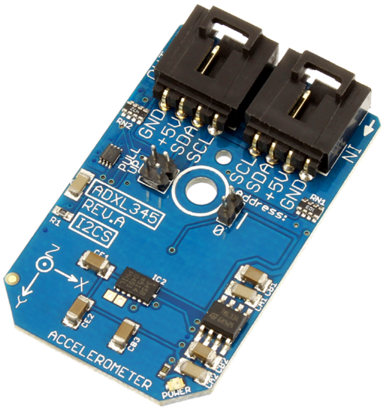


Figure 13. *Particle Photon 3 Axis Accelerometer*

https://store.ncd.io/product/adxl345-3-axis-accelerometer-13-bit-i2c-mini-module/

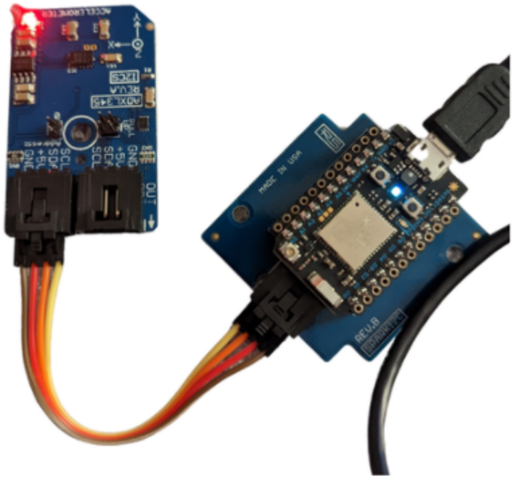


Figure 14. *Particle Photon Connected to Accelerometer*

The three components of the microcontroller, accelerometer, and force-position sensors needed to be wired together to function. It was necessary that the wiring was also unintrusive to the helmet's ergonomics. The team settled on a simple perf board design to meet these requirements and create the circuits that serve as the central connectivity unit for the helmet's electrical integration. The microcontroller was connected to an I2C shield with a four-pin JST header attached to the ground, 5 volts, serial data, and serial clock pins. The accelerometer was connected to the microcontroller using a JST header on the shield without occupying any of the available pins on the microcontroller, leaving them open for the necessary force-position sensors.

The force sensors included three connectors: two drivelines and a sensing line. Each sensor connected to two corresponding sets of two digital and analog pins on the Photon. The Particle Photon housed eight analog pins (A0 to A7) and eight digital pins (D0 to D7). According to the Photon datasheet, A6 and A7 map to the ADC and PWM pins but could also be configured as analog inputs. Because each corresponding sensor used two analog and two digital pins, the team was able to incorporate four force sensors in the design. The following figure illustrates the circuit between the force-position sensors and the microcontroller.

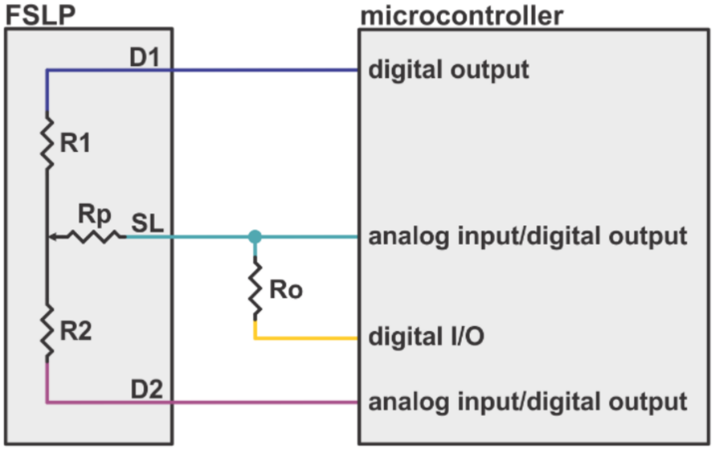


Figure 15. *Force sensor-microcontroller circuit.*

https://www.pololu.com/product/2730/pictures#lightbox-picture0J5359

Four instances of this circuit were recreated (one for each of the four force sensors) on an eight-by-two-centimeter perf board. For R0, we opted to use a 5.1 kΩ resistor because the equipment documentation recommended between 4.7 and 10 kΩ. For easy accessibility in building the design and mounting the electrical boards to the helmet, we designed a quick way to connect and disconnect the Photon, the perf board, the force sensors, and any jumper cables in between. Male pin headers on the perf board were connected to the female end of a jumper cable. Along the long edges, four four-pin male headers were lined up on one side for connectivity to the microcontroller, and four three-pin headers were aligned on the opposite side to connect to the force sensors. We soldered each pin of the three-pin headers to its corresponding pin on the four-pin header, directly across from one another, respectively. The following figure visually shows the setup of our perf board.

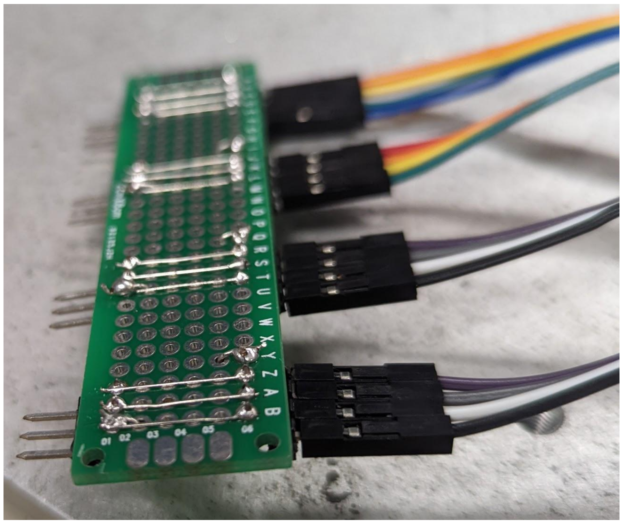


Figure 16. *Soldered Connections on the Integrated Circuit.*

In other words, the left-hand side connects to the force sensors, and the right-hand side connects back to the Photon. Row Z connects driveline 1 to the digital output; row A connects driveline 2 to the analog input/digital output; row B connects the sense line to the second analog input/digital output and connects to the fourth pin on row Y across our 5.1kΩ resistor (which has been placed on the other side of the board).

With all the physical sensors completed and ready for installation in the helmet, the project's next step involved creating an easily accessible place to read the data. Our team decided that making an application for our helmet would be the most efficient way to display data in real-time. When creating an application, the first consideration was in which platform and language would the application be coded. We considered the two most popular platforms for coded applications, Apple and Android. Each platform had its own application development software, which provided a foundation for building the application. Initially, the team intended to create an Apple application, as most of the team use Apple cell phones. However, Apple's Alphaco development software presented a significant learning curve, with obtuse tutorials that eventually culminated in a steep publication cost. By comparison, Android's development studio was very user-friendly, with a built-in virtual machine that simulates an Android phone to test the application on the go. Furthermore, the primary language for Android Studio is Java, with which our developers are much more familiar.

With the platform and language decided, we needed to determine the functionality. Our application was required to do the following:

1. Read data input from the connected microcontroller
2. Process that data according to our research
3. Display the data in real-time to the user

The team employed an application programming interface (API) to complete the first part of the functionality. API's are used to handle any messaging between software programs via pushing information to a given URL and then receiving that data with a "get" call. The photon already pushed its data to an API, so the application needed only to grab the data from that URL. Processing the data was even more straightforward. In the app, we set data constraints based on our research and executed different commands based on whether the incoming data matched or exceeded those predetermined values. These various commands were set to handle real-time data display, changing a displayed number and color to indicate the severity of a post-accident injury correctly. We had set green for readings below 30G, yellow for readings between 30G and 58G, orange between 58G and 80G, and finally red for anything beyond 80G. Figure 17, a visual from the University of Michigan was the main source for how we determined our thresholds for each range.

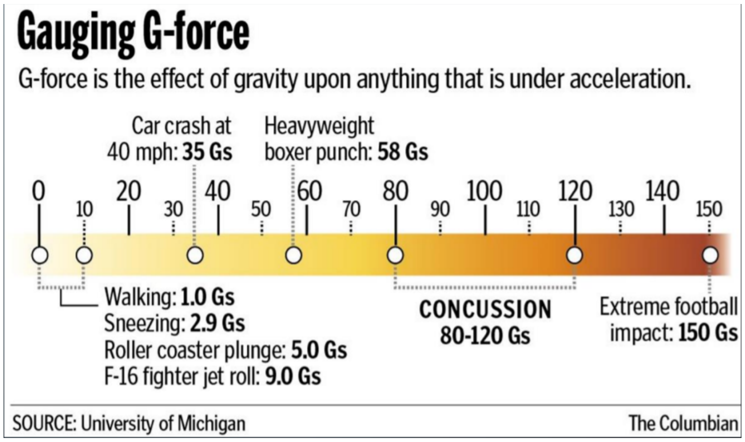
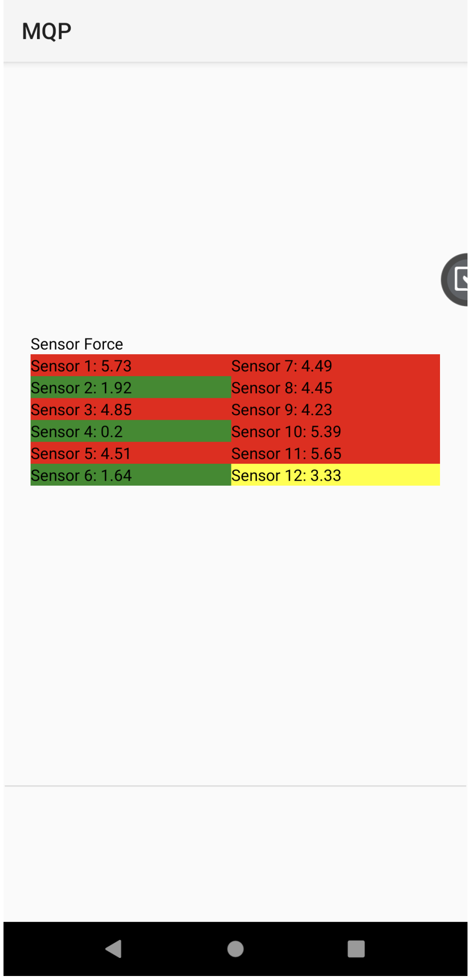


Figure 17. *A Comparison of G-Force to Various Human Activities.*

The Columbian,Gauging G-Force. 2012. University of Michigan, Ann Arbor. Web. 31 Mar 2013

For the final process, we once again employed an API. An early version of the application is shown in Figure 18.



Sensor Force

Sensor 1: 5.73	Sensor 7: 4.49
Sensor 2: 1.92	Sensor 8: 4.45
Sensor 3: 4.85	Sensor 9: 4.23
Sensor 4: 0.2	Sensor 10: 5.39
Sensor 5: 4.51	Sensor 11: 5.65
Sensor 6: 1.64	Sensor 12: 3.33

Figure 18. *Prototype Application with Dynamic Colors.*

We encountered a few critical limitations with our application and components. The Particle Photon, which we hoped would be simple to code and modify, was unable to connect to the certificate-based authentication of the university's Wi-Fi. Because the photon had to be coded over Wi-Fi, the access issue with the university's authentication program meant that all testing while running the Particle Photon's programs needed to be done on home internet networks. Furthermore, the Photon lacked Bluetooth capability, a much easier way to transmit data, especially in areas with no local internet. We attempted to connect the Photon to mobile cellular data, but the success was finicky and offered a significantly lower efficiency rate. The force-position sensors presented yet another limitation. These sensors are not designed to handle much more than a touch, presenting a severe drawback to measuring large amounts of force. However, force-position sensors added the crucial element of identifying impact location, for which function they performed well.

3. Broader Impacts

The Engineering Code of Ethics summarizes three main points: Use knowledge and skill to enhance human welfare, be honest and impartial, and strive to increase the competence and prestige of the engineering profession. The goal of this MQP was to create a technologically advanced safety device to improve the protection of recreational cyclists. This concern for human welfare speaks to the first point of the Engineering Code of Ethics. To the second point of honesty and impartiality, the team has divided work based on area of study (electrical versus mechanical engineering) with evenly distributed workloads among all team members. Furthermore, an open line of communication is kept among group members and with mentors. Finally, the resultant safety helmet increases the prestige of the engineering profession by introducing a viable and advanced piece of equipment for a specific athletic community. This MQP focused on the prevention and real-time diagnosis of potential head injuries, and future MQPs may add on different new cycling safety equipment, engineered and programmed to protect other body parts. This engineering team has opened a new avenue for safety equipment and the protection of a community of cycling enthusiasts.

Accidents during recreational biking are the leading cause of serious head injuries treated in hospitals each year. Helmets have been proven to significantly reduce the risk of fatal injuries. In a study from the American Journal of Surgery, wearing a helmet reduced the risk of serious injury by 51%(Cohen). The goal of this project is to further reduce the risk of serious head injuries by allowing cyclists of all ages to determine the severity of any impact to the head in real-time. The sensors in the bike helmet monitor impacts and connect via an app to let users immediately know if medical attention is necessary. In absence of diagnosis, riders frequently crash and continue riding without knowing they are concussed, enabling more extensive brain damage. Our helmet will substantially reduce the risk of fatal head injuries amongst all ages and types of cyclists.

In order for a bike helmet to be sold in the United States it must pass the standards set by The Consumer Product Safety Commission (CPSC). This is legally required. Some countries follow the CPSC standards, while other countries have their own sets of standards that they must follow when it comes to bike helmet safety. The CPSC standards must be followed for any helmet sold in the USA after March 10, 1999.

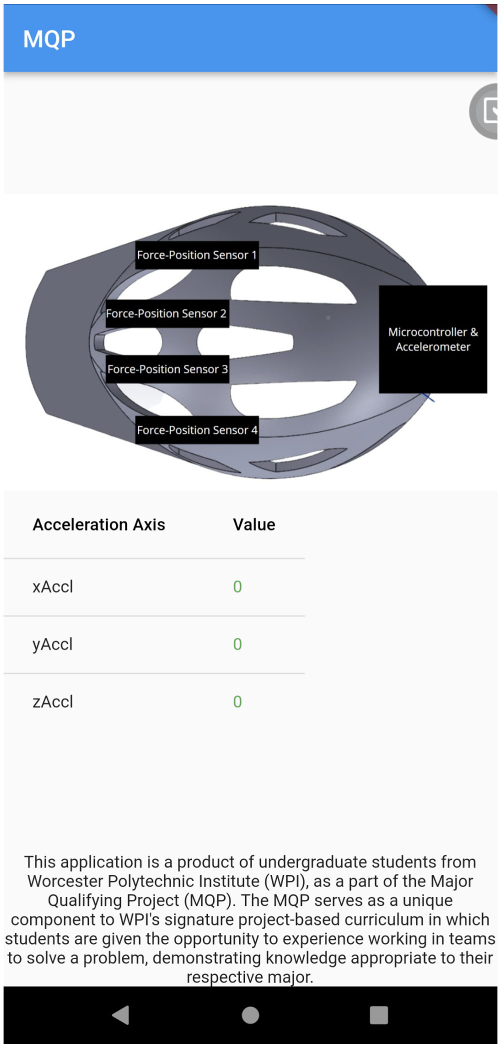
In order for a helmet to pass the CPSC guidelines the helmet must pass a drop test. To do this, a helmet must be placed onto a test dummy head and then dropped from a specified distance, usually somewhere between one to two meters, onto an anvil. A flat anvil is used when a helmet is dropped from two meters and a curved anvil is used when a helmet is dropped from 1.2 meters. Like any other test, a helmet can either pass or fail this drop test. In order to judge this an accelerometer inside of the test dummy head is used. If this accelerometer reads more than 300 G of force then the helmet is deemed unsafe. All helmets must pass this test when they are hot, cold, and wet.

In addition to the drop test, all helmets also require that the straps and buckles meet a certain strength as well. Sometimes tests will also be used to see if a helmet will roll off of a head when force is applied from one side or the other.

The economic impact of this helmet is the potential to greatly affect the market space for technology driven helmets. At the moment, most of the technological improvements have been seen through mechanical innovations. However, by incorporating sensors and changing the helmet into wearable tech, the entire market space changes and pushes the envelope of what's possible. While this might not affect all market competitors, bikers are known to be a consumer looking for the best innovation for their ride, and this helmet will greatly appeal to them in terms of safety and speed. This helmet will cost more then traditional helmets for consumers, as the sensors increase the price and elevate the offering, but we are sure that there is a target consumer and a market share waiting for this type of helmet to emerge.

4. Results & Discussion

Our first test was to ensure the mobile application was formatted and filled with the expected information. First, the application was run a few times with colored tables to feel its functionality. We then moved to more detailed testing, ensuring our threshold code worked by submitting random values for the application to display. To test the API, we replaced those random values with the actual sensor inputs from the force-position sensors and accelerometer to verify that the application code recognized the information. The application ran successfully with the desired display and data, as expected. However, one limitation of the application was the fact that it only would update with new data in the table of acceleration approximately every eight to fifteen seconds – significantly longer than what we expected. The console outputs new data from the accelerometer about every two seconds, with published timestamps on each reading for reference. We concluded that the reason for the delay is in the nature of the software we used for the API calls.



Acceleration Axis	Value
xAccl	0
yAccl	0
zAccl	0

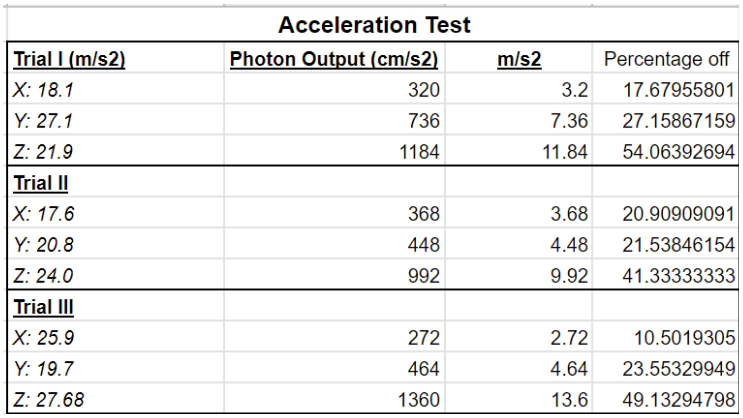
This application is a product of undergraduate students from Worcester Polytechnic Institute (WPI), as a part of the Major Qualifying Project (MQP). The MQP serves as a unique component to WPI's signature project-based curriculum in which students are given the opportunity to experience working in teams to solve a problem, demonstrating knowledge appropriate to their respective major.

Figure 19. *Second Prototype of Application*

Due to the aforementioned complications with connecting the microcontroller to the University's Wi-Fi network, the team was unable to perform plausible testing procedures in a lab environment. Instead, our team ran a series of two different at-home tests for the sensors – the first test for the accelerometer and the second for the force-position sensors.

On the accelerometer test, we elected to use the mobile app, Accelerometer, developed by Microsys Com Ltd, which served as the control in each trial. This allowed us to observe the acceleration our phone was moving at in the X, Y, and Z axes respectively. The app plotted the acceleration over a real-time time domain for each axis. Then we attached the accelerometer to the phone so both devices would share the same acceleration for any applied motion. The results from the readings were compiled into the chart below. Because this was the first time we were able to test the accelerometer, we expected there to be some errors in the data. To examine the accuracy of our data we created the "Percentage Off" column and calculated how far the accelerometer readings were in comparison to the control.

Table 1. *Acceleration Test Results*

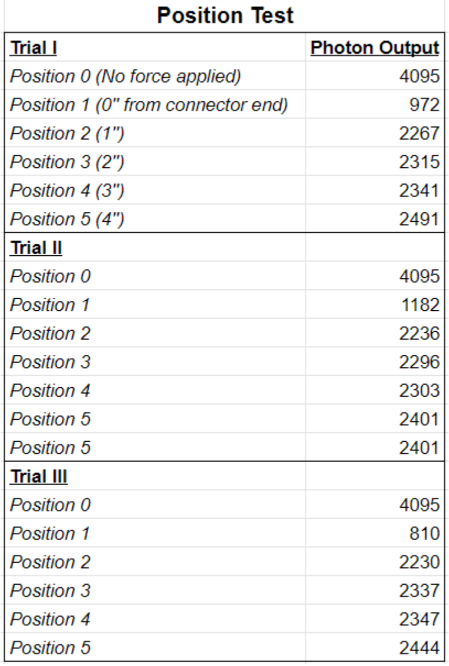


Acceleration Test

Trial I (m/s2)	**Photon Output (cm/s2)**	**m/s2**	Percentage off
X: 18.1	320	3.2	17.67955801
Y: 27.1	736	7.36	27.15867159
Z: 21.9	1184	11.84	54.06392694
Trial II			
X: 17.6	368	3.68	20.90909091
Y: 20.8	448	4.48	21.53846154
Z: 24.0	992	9.92	41.33333333
Trial III			
X: 25.9	272	2.72	10.5019305
Y: 19.7	464	4.64	23.55329949
Z: 27.68	1360	13.6	49.13294798

Unfortunately our readings were not accurate, with the best accuracy being in the 40%-50% range for readings in the Z axis, and the worst being the readings in the X axis ranging from 17%-21% accurate. However, this test demonstrated that the sensor is functional. Two potential options to address this would be fine-tuning the program/calibrating the sensor to attempt getting more accurate results, or testing in a more sound lab environment for more accurate control acceleration values. Another issue could be the hardware itself – the accelerometer may provide inaccurate results which would warrant using higher quality equipment for the project.

For the force-position sensor, we conducted three trials of tests on one sensor. With the sensor set on a flat surface and the sensing side facing up, we pressed a 0.375 inch-diameter circular surface on five evenly-spaced points along the sensor. Because the force component of the sensors was less relevant, with the accelerometer measuring G-force from impact, we elected to focus on ensuring functionality of the position readings; therefore, the pressure applied to each of the five points along the sensor was not relevant in this procedure. The results from this experiment are charted below.



Position Test

Trial I	**Photon Output**
Position 0 (No force applied)	4095
Position 1 (0" from connector end)	972
Position 2 (1")	2267
Position 3 (2")	2315
Position 4 (3")	2341
Position 5 (4")	2491
Trial II	
Position 0	4095
Position 1	1182
Position 2	2236
Position 3	2296
Position 4	2303
Position 5	2401
Position 5	2401
Trial III	
Position 0	4095
Position 1	810
Position 2	2230
Position 3	2337
Position 4	2347
Position 5	2444

Table 2. *Position Test Results*

Unfortunately, we were unable to conclude meaningful results from our tests on the force-position sensors. The program for the sensor appears to be producing raw values, rather than a measurement of distance or length that we would then compare with the control distances. It does seem as if the raw reading increases as length from the end of the sensor increases, indicating that the raw readings alone may be accurate. The values from position to position between each trial fall within the same ballpark (the range of readings for position 5, as an example, calculates to 90).

5. Recommendations

This section details different ways in which this product could be improved for a commercial model. The areas of improvement discussed in this section are accelerometer choice, position sensor choice, mechanical design, and user experience.

5.1 Accelerometer

As mentioned in Figure 17 above, concussions occur between 80-120 Gs. Therefore, in order to have the best user experience, we would like to be able to measure between 50 and 150 Gs so that possible concussions, as well as injuries much more severe, could be detected by our smart helmet. The accelerometer chosen for this project was an H3LIS331DL3, 3-Axis accelerometer with a programmable range of ±100, ±200, or ±400 Gs. The basic range of the accelerometer was ±100 Gs, and due to time constraints, the team could not program it to a 200 or 400G range.

For a commercial version of this project, the accelerometer would have been programmed to the 200G range, so that the smallest and largest possible values of concussion impacts would be detected. Another option would be to use an accelerometer whose base range is 200G and does not need to be programmed. An example of such an accelerometer is an ADXL377, as shown in the figure below. Updating the output range of the accelerometer used would greatly impact the accuracy of measurements taken, as well as create a product that operates within its intended use.

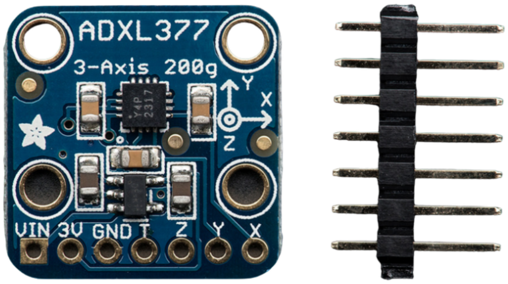


Figure 20. *ADXL377 ±200G 3-Axis Accelerometer*

https://www.adafruit.com/product/1413

5.2 Force-Position Sensors

The following component that would be updated if this product were created commercially would be the position sensors. As stated in the Electronic Processes part of the Methodology section, these sensors were originally purchased to output force data as well as position data. This would tell the team what part of the head was hit on impact, as well as how hard the hit was. Unfortunately, the position sensors purchased had a force sensing capability meant only for a light touch, such as how one would treat the screen of a smartphone. After realizing this, the team used these sensors only to show position, however this reading was difficult to decipher.

Moving forward, one would want a position sensor that could measure extreme forces, one that would not break at a high level of impact. However, after much research, the team was unable to find a sensor of both capabilities. Another option would be to create an extra system within our electronic design that encompasses both the position sensor strip and mini force sensors. Our design already includes the position sensor strips, so the only addition would be the mini force sensors. Although this is a good idea in theory, it becomes much more complicated in practice. Many more electronic connections would have to be made in order to incorporate the force sensors into the design, which would create an even bulkier load on the back of the helmet. Not to mention, the added cost of purchasing the force sensors.

An additional idea would be to add more accelerometers, one on either side of the helmet, as well as the existing one in the back. Theoretically, all three of these accelerometers would be 3-axis, and would show a different amount of force along each direction (X, Y, Z) during an impact. Then, these could be used as position sensors since the (X, Y, Z) direction with the highest force after impact would indicate the (X, Y, Z) location of the impact. There are many other possibilities in improving the position-force sensor design of this product, however, due to time constraints, only a few options could be explored.

5.3 Mechanical Design

The mechanical design portion of the product includes the casing for the electronics, as well as how comfortable the helmet is with the addition of sensors on the inside. As shown above in the Mechanical Processes portion of the Methodology, the current housing for the electronics is bulky and awkward. In order to create a less obstructive housing, there must be a better way to either stack the electronic components or create a housing that is not a rectangle.

The current housing is a box, connected to the helmet by a GoPro connector. One way to eliminate this inconvenient design would be to create a rounded shape. Since the helmet itself is round, an additional “bump” to the back of the helmet would look much less bothersome than a plastic box hanging off the back.

The stacking of the electronic equipment is another option to consider in making this mechanical design easier on the eye. Currently, within the housing, the PC boards are literally stacked on top of each other separated by a layer of foam. One way to break up this design would be to spread out the components along the back of the helmet, in order to flatten them to the helmet. Then, a shield could be created, almost like a back plate to the helmet, which would not only hold the components in place, but also protect them from damage and weather. One consideration in updating the design in this way would be the flexibility of the connecting wires, and their ability to reach around the helmet a little further of distance to their counterparts. An argument for replacing stiff wires could definitely be made, and this back plate design is a suitable option for evaluation in the future.

5.4 User Experience

Other than the comfort of the helmet, the user experience encompasses the ability to change the battery to our system, as well as how easily the mobile application functions. In the future, an important addition to the mobile application would be to ensure that any information shared by the user is treated with proper care. This includes security and privacy capabilities on personal information and more.

6. Conclusion

The purpose of this project was to design a bicycle helmet that enhanced safety through the use of Internet-of-Things technology. Our initial research determined bicycling was an untapped market for smart wearable helmets and that continuously updating sensors could detect the most common injuries in that market. Force-position sensors and an accelerometer served to identify and measure head injuries while biking. We used CAD simulations to approximate the stress the helmet could take with those parts in mind. Finally, we created an application that could be updated modularly to include a wide variety of smart bicycle safety equipment. Improvements to the parts and code will help the product reach its full potential as indispensable cycling safety equipment.

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