# Identifying Magnitudes of Acceleration and Rotational Forces that Impact the Head when Mountain Bike Riding

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## Authorship

Work was divided equally by having each group member focus on a specific part of the project. Samuel Ott oversaw producing the sensor and wrote the code for its functionality and was mostly in charge of its design and specifications. Benjamin Pinto did most of the literature research and identified and planned the data analysis for the forces involved. The bulk of the MATLAB code was written by Samuel Ott, and most of the planning involved in the creation of this experiment was done by Benjamin Pinto.

# Acknowledgments

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# Abstract

Sub-concussive impacts in sports pose significant health risks, yet limited data exist on their magnitude and long-term effects, particularly in mountain biking. This study aims to extrapolate accelerometer data from mountain bike trails into equivalent concussive impacts using the Head Injury Criterion (HIC). Two bikes, a hardtail and a full suspension, equipped with helmet-mounted sensors, were ridden down the Cascades trail in Worcester, Massachusetts. Acceleration data were collected and processed using MATLAB to calculate HIC values. Results were compared to injury thresholds established by the National Highway Traffic Safety Administration (NHTSA). The average HIC for the hardtail was 274.94, and for the full suspension, 212.73, corresponding to level 1 injury severity. Although consistent with previous studies, limitations include the small number of runs and the inability to visualize internal brain damage. Further research is needed to understand the long-term effects of sub-concussive impacts in mountain biking. This study sheds light on the potential health risks associated with sport and underscores the need for continued investigation into injury prevention and rider safety measures.

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## 1. Introduction

Sub concussive impacts are a very consistent source of mild, yet long-term injuries for athletes of many sports. There are several sources of death linked to the exposure of low, but consistent sub-concussive impacts and yet a surprisingly little amount of information covering these forces.[3] Few sources address the potential magnitudes of accelerative forces and translate this data. Most of these articles and experiments attempt to analyze these ranges of acceleration, conform themselves by logging this information and simply observing different levels of risks for mild traumatic brain injury.[4] The purpose of this project is to extrapolate the data from an accelerometer attached to the helmet of a bike rider, across the entire an entire downhill path and envision it as a single concussive impact. This is to compare the data obtained and existing data by using the Head Injury Criterion established by the National Highway Traffic Safety Administration.

There is a significant gap in the current understanding of cognitive health in terms of how outside influences affect the brain. This shortfall is especially seen when it comes to subconcussive impacts and their effects on cognitive well-being. In this field, most research has been done on major impacts causing concussions and some on smaller bursts within the brain. Nevertheless, even within these well-studied fields, comprehension of the less studied small repetitive impacts which can lead to subconcussive damage remains limited.

Most documented concussion cases are associated with high impact sports hence little has been studied concerning continuous shaking and impacts on the head such as encountered during mountain biking. However, most research in this area looks at well-known effects from sports while this project focuses uniquely on subtle enduring consequences of repetitive head movements in Mountain Biking. The study seeks to determine the levels at which brain injury may be sustained due to multiple non-concussive impact events through applying physics concepts to analyze accelerations and vibrations occurring in the cranium.

The focus of this research is not about injuries only, but it aims to develop a sensor that can allow individuals to measure data from their mountain biking experiences in order to assess the level and magnitude of forces impacting their head. The tool is meant to gauge the head vibration levels, thereby providing hints on potential brain injury risks similarly contributing towards better understanding of cognitive health within the context of physical activities.

Moving forward, the project acknowledges that historically study into concussive injuries has been heavily skewed towards high impact sports such as American football. However, there is little comprehensive information regarding subconcussive injuries arising from repetitive yet less intense impacts such as those experienced in downhill mountain biking. Such a need for exploration becomes clear since unlike concussions, subconcussive injuries may be less symptomatic but have potential long-term effects including memory loss, permanent brain damage and interruptions in neural pathways.

However, a careful exploration of available literature shows a lack of documentation regarding head impacts in downhill mountain biking. This deficiency is further emphasized when considering subconcussive injuries as they are overshadowed by concussive ones within the research domain. On the other hand, research tends to focus on concussive injury due to its instantaneous expression and obviousness; contrary to this, sub concussive effects are equally important, calling for more inquiries concerning the factors that cause them and their results.

To address this gap in knowledge, an extensive review of many studies on head impacts was undertaken, which revealed a critical neglect of the subtleties of head impacts in downhill mountain biking. Despite its potential contribution to cognitive health at large, this oversight may arise because it is believed that less contact sports have fewer severe brain injuries. Nonetheless, this assumption overlooks the cumulative effects minor head trauma can have on one's body given how subtle but potentially devastating subconcussive injuries can be.

This study intends to propose a comprehensive experimental phase aimed at addressing the lack of subconcussive injury research. To this end, sensors will be deployed in this phase to record and identify different forces that may affect the head during mountain biking. The detailed approach involves studying directional vectors such as horizontal and vertical displacements to know effects on the helmeted head. These data collected through strategically placed sensors will offer an intricate understanding of the forces involved, thus helping differentiate between concussive and subconcussive injuries.

This paper, with reference to existing literature on sports-related head impact sensor studies, recognizes the importance of descriptive data obtained through accelerometers. These sensors ascertained not only force directions but also twisting, jerking and destabilizing movements on the impacted heads comprehensively. This project achieves this by quantifying and categorizing these forces to contribute to a better understanding of what causes injuries thereby facilitating the production of better helmets and protective gears.

This project also considers the historical emphasis on studying concussive injuries as they have clear symptoms and long-term damage. However, subconcussive injuries have been overlooked in research due to their subtle nature. Nonetheless, subconcussive injuries demand a closer look regarding their long-term damages on neural pathways especially within mountain biking context. While these are some of the difficulties associated with detecting and studying subconcussive injuries, this study is aimed at adding to the wider knowledge about forces and effects involving extreme sports.

During this project's progress, two sensors will be developed specifically for monitoring the participant's head and bike. These sensors will record and identify forces impacting the head during mountain biking to determine a threshold that differentiates between a concussive injury and a sub-concussive injury. This is important since it is not clearly known what level of force can cause concussion, but it has been estimated that ten times gravity might cause irreversible harm.

When calculating and determining forces acting on the head, it is imperative to consider variables such as velocity, directional speed and the distance covered before a counteracting force is applied to the participant. Any understanding of the potential for injury to result from the sudden stop of a high-speed moving head begins with a comprehension of jerk. Nevertheless, this analysis will be complicated by the myriad directions that can be seen when one tries to navigate up and down mountain paths; however, an evaluation of the manner in which the participant’s head was propelled will have to consider both horizontal and vertical forces placed on it. To collect such information, a sensor must be fitted at an appropriate position on the participant’s head. It will then be fed into the specially designed equation which will help in organizing and simplifying this intricate system of forces encountered during mountain biking into a comprehensive interpretation.

## 2. Literature Review

The literature review presented in this study delves into the multifaceted domain of cycling-related injuries, with a particular emphasis on subconcussive impacts in downhill mountain biking (DMB). Despite the scarcity of professional literature in this area, the existing studies provide valuable insights into the forces involved and their potential consequences for cyclists' cognitive health. Through the examination of biomechanical factors, such as accelerations and rotational head movements, researchers strive to elucidate the distinction between concussive and subconcussive injuries, as well as their long-term implications. Furthermore, the review explores the challenges associated with detecting and studying subconcussive injuries, emphasizing the need for further research to enhance cyclists' safety and well-being.

### 2.1. Understanding Subconcussive Injuries in Cycling

The main concern with the subject of this project, subconcussive injuries, is that there tends to be little information in a professional environment related to this subject, this is particularly true in the realm of biking. Yet, there are many tangential studies that can be used to glean some insight into what forces are at play, and what magnitude of forces one can expect would cause harm to the brain of a cyclist. It is important to state that many of these studies use accelerations, and how these quick and brutish changes in speed can affect the head and neck of a cyclist. Some other research papers focus more on actual concussive injuries, which the point of their inclusion helps garner a clearer line between concussive and subconcussive injuries.

The particulars of these differences specified can be seen in the document “Biomechanics of Concussion” where it is explained that contact and inertial forces are those to blame in the cause of concussions and injuries within this vein. The note of importance lies in inertial forces, this project postulates that consistent inertial forces of a lower magnitude may cause internal injuries. Whereas the document states that contact, the act of one’s head striking against another blunt object, only make up the rarer and more severe of effects, whereas injuries caused by inertial or acceleration loading result in milder injuries, but tend to occur more, in or not in tandem with contact. The document states that this is also coupled with rotational acceleration, which is what occurs in rapid erratic movement of the head; this can generate shear forces throughout the brain, according to the article, giving more credence that small to medium magnitude forces that consistently affect a cyclist can cause legitimate harm.

This document works together with those that directly address rotational head accelerations and translational accelerations. There are several of these articles that help profile and understand the magnitude of these forces in youth and older bike riders. One study that goes into profiling and giving an idea as to what we should expect in our results is the “Profiling of translational and rotational head accelerations in youth BMX with and without neck brace”. This is a particularly pertinent document in this project's background study, as it helps demonstrate the results of a similar experiment. It mostly focuses on rotational movement in degrees, as well as the number of accelerations that resulted in erratic head movement and the magnitude of these accelerations. It is even more helpful that they studied both with a neck brace, and without one since it helps us visualize and compare the differences between forces with and without protective equipment.

### 2.2. Implications and Challenges of Subconcussive Injuries

This document is followed by a similar document that helps bring more clarity and relates more closely to the project. The document is an original research article by the School of Sport and Wellbeing, University of Central Lancashire and the School of Health Sciences, University of Salford, both in the UK known as “The Magnitude of Translational and Rotational Head Accelerations experienced by Riders during Downhill Mountain Biking”. This document provides information similar to that of the previous document, in which most of what we see in terms of results is acceleration in gravitational acceleration, as well as angular velocity in rad/s as it once more focuses on angular acceleration determining that as the main source of mild concussive injuries, but more interestingly, subconcussive injuries. Interestingly, the study determined that the results showed a higher level of angular acceleration and velocity than in other similar cycling sports. The document also suggested that riders are at risk of sustaining minor traumatic brain injury just by riding downhill due to previously reported thresholds in what a brain can sustain and how their own results had averages higher than these thresholds.

This observation of the angular accelerations and velocities that help give identity and meaning to the forces that are recorded throughout the experiment is immensely valuable towards understanding the impact that these consecutive forces can have on the human brain. There are other articles that help provide a similar oversight, with a particular one known as “A Review of Cyclist Head Injury, Impact Character Characteristics and the Implications for Helmet Assessment Methods” giving data that can be compared to that of previous documents. With head impact speeds reported as values of meters per second of 5 to 16, with their concentration holding a smaller range of 5 to 8 meters per second, these values help establish a differentiating baseline between subconcussive and concussive injuries. Furthermore, the angle ranges caused by jerking movement is also provided as a range of 10 to 80 degrees, with most of the values recorded being between 30 and 50 degrees. The focus of this article is to provide an idea of how the helmet can affect differences in head jerking movement, and angular acceleration, mostly to understand where the weaknesses in helmet protection lay. Most importantly though, this information will help calculate and compare our data with that of the article to understand how much of the angular acceleration and velocity affect the brain and how much is mitigated and affects solely the helmet.

### 2.3. Evidence of Dizziness and Vision Impairment

A challenge found in the design and planning of this project was how one could determine that there in fact had been some manner of damage to the skull or brain caused by subconcussive injuries. This is attributed to various things, such as the fact that the truly harmful effects of subconcussive injuries are not perceived until months or years after they started occurring, and generally not after a single subconcussive injury. Fortunately, a similar research paper aiming to solve questions not dissimilar to those postulated within this paper aimed to test the effects on executive function after downhill mountain biking. While also helping provide specific figures on the amount of g forces required for head accelerations to cause harm, but more importantly they discuss at length the effects and impacts of subconcussive injuries. The effects of subconcussive impacts from simply riding downhill was tested through what is known as a Stroop color-word test, which was meant to test changes in executive function which could suggest that there have been injuries to the participant’s brains by testing for changes before and after riding downhill.

The study conducted by the researchers aimed to investigate the prevalence of vertigo among downhill mountain bikers (DMB) and road cyclists (RC) following competitions or training sessions. The survey involved 102 DMB riders, 79 road cyclists, and 73 control participants, evaluating the occurrence of vertigo in daily living activities and post-riding events. Surprisingly, DMB riders and road cyclists did not report higher instances of vertigo during daily activities compared to controls. However, the study revealed notable differences concerning age and post-riding vertigo. DMB riders aged over 30 exhibited a higher risk of reporting vertigo compared to age-matched road cyclists, emphasizing a potential age-related vulnerability. Moreover, after competitions or training sessions, DMB riders were more likely to report vertigo compared to road cyclists, suggesting a distinct association between the sport and vertigo incidence. Causal factors differed between the two groups, with DMB riders attributing vertigo to crashes with head trauma, while fatigue was implicated in road cyclists. The findings underscore the importance of understanding vertigo's prevalence and associated risk factors in cycling disciplines. For older DMB riders, the study suggests a need for heightened awareness of vertigo, potentially stemming from cumulative impacts experienced during their careers. In contrast, for road cyclists, vertigo is linked to exertion-related disturbances of homeostasis. These insights can inform injury prevention strategies, emphasizing the need for DMB riders to recognize the possibility of vertigo post-riding activities and take appropriate precautions. Overall, the study sheds light on the nuanced relationship between cycling disciplines, age, and vertigo occurrence, contributing valuable knowledge to enhance cyclist safety and well-being.

# 3. Project Strategy

## 3.1. Initial Client Statement

Subconcussive impacts are prevalent yet unstudied in mountain biking, partly because there is little in their identification and discussion of their long-term effects. To somewhat have an idea of the impact of these forces, they needed to be measured and extrapolated into scale for measurement. The team's goal was to craft a sensor capable of identifying the forces at play while downhill mountain bike riding, and scale them into their potential effects.

## 3.2. Design Requirements (Standards)

Based on our client statement, a list of objectives was designed through a successive identification of requirements and understanding of how to quantify the data obtained. Initially it was the first thought of what data can be used to approximate or help set a scale of the potential effects that may be occurring inside the brain. For this purpose, acceleration data of the head's specific movement was used as a form of identification of the forces that may be impacting the brain. The acceleration data should be a realistic representation of the forces at play and must contain as little noise and drift as possible for the measurements to be accurate. Then, this data must be placed against a thoroughly tested scale or unit that can somewhat quantify the magnitude of damage or level of subconcussive impacts at play. The entire process would require multiple tests in order to ensure that the sensor is reliable, and it should be small and wearable by the user in a way that does not impact riding ability.

*Table 1: Specifications determined by our design requirements*

| **Specification** | **Purpose** |
|---|---|
| Subconcussive impacts have long term consequences through small mediated but consistent impacts. | Ensures that forces that cause these impacts are minimal yet stacking. |
| Obtain measurements of magnitude and consistency of forces that impact the head while mountain bike riding. | Clear visualization will allow for easier quantification of damage accumulation |
| It must have the ability to measure consistently across the entire trail. | Repetition and number of forces can be consistently measured across the entire trail. |
| An accelerometer connected to an Arduino can measure every force. | Ability to observe and record forces that impact the head every 10 milliseconds. |
| Head Injury Criterion quantifies impacts into a scale of observable chance of head injury and concussive impact. | Ensures data can be quantified into a concussive impact, which has more research available to it. |

| | |
|---|---|
| Number of samples should be consistent for comparison | The same trail will be used over multiple trials, and the Arduino will have capability of stop and starting measurements. |
| Forces recorded should have as minimal noise and authentic as possible | Filters will be utilized to remove noise |

### 3.3. Design requirements (technical)

The sensor must be capable of detecting acceleration magnitudes of exceptionally low levels, specifically of around 1-5 meter per seconds squared. It must also have the capabilities of logging the accelerative forces in a 3-D plane, The sensor must be able to differentiate and log different runs. It must also have an independent battery and be easily wearable on the head by the bike to not be interfered with. The data must also be easily transferable to a computer to run statistical analysis and proper analytical tools through it. The sensor must also be affordable, and easily assembled.

# 4. Design Process

## 4.1. Concept Mapping

Planned idea of calculator to interpret results, but too many variables; originally purchase a sensor, specifically concussion sensors but we could not find any that could detect subconcussive impacts. Decided to do 2 sensors instead of one for data comparison (accuracy). Made our own sensor using an Arduino accelerometer and gyroscope (accelerometer for impacts and gyroscope for rotational for 6 degrees of freedom (3 dimensions and 3 axes)

The original plan for the project was to create a calculator that could predict the likelihood of cognitive function impact based on inputs the user would give. These inputs include variables such as trail length, net change in altitude, type of bike, body mass index, height, and type of bike. However, while attempting to construct the calculator it was discovered that there were too many variables that could even include wind speed of that day and the aerodynamics of the system, so the calculator idea had to be modified to something that could be done as part of a future MQP.

For the data collection, the original idea was that there would be a single sensor on the person. The ideal sensor would be sensitive enough to be able to detect tremors in the system. The sensor was going to be outsourced, as the hope was to find a sensor that would be able to measure the motion of the system to the point where alternans that could correspond to cognitive impact would be noticed. However, after extensive searching, such a sensor could not be easily found.

Since it was determined that there was not a sensor that would adequately measure the motion of the subject, a custom sensor was made using an Arduino MKR Zero board with

MKRIMU shield which provided acceleration in all six degrees of freedom  It also was decided that a second sensor on the bike would also be utilized as a second set of data to compare the motion of the head to the motion of the bike. It also was believed that a second sensor would help with accuracy of data being collected.

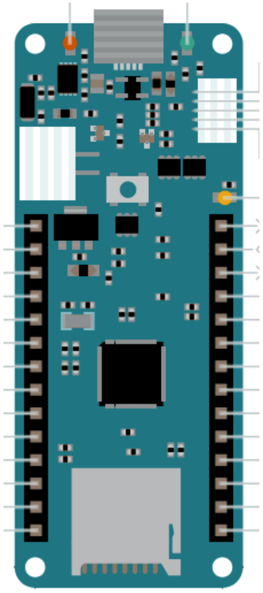


*Figure 1: Arduino MKR Zero board*

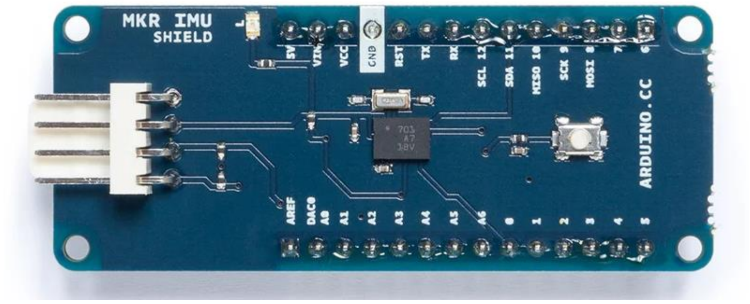


*Figure 2: Arduino MKR IMU sensor*

Once the trials are completed, the data would be analyzed through MATLAB to find correspondence between certain variables and cognitive functions. As many variables that could be controlled would be controlled, changing only one at a time to see which ones have the highest correspondence to cognitive function impact.

### 4.2. Methodology

There were several important steps taken to both gather data and authenticate the data we were obtaining from our sensor. By meticulously evaluating the accelerometer and gyroscope drift through controlled experiments, we ensure the accuracy and reliability of the sensor's measurements. These tests establish a baseline for the sensor's performance, allowing us to mitigate any potential errors or inconsistencies during data collection on the field. Additionally, the on-site testing methodology conducted on the Cascades trail in Worcester, Massachusetts, aims to capture real-world scenarios of mountain biking. Through multiple runs on distinct types of bikes, we seek to understand the diverse forces exerted on the head during downhill descents. Moreover, the construction of the sensor's code plays a pivotal role in data acquisition and analysis. By implementing algorithms tailored to interpret accelerometer and gyroscope data, we can quantify and categorize the forces experienced by riders, thus facilitating a comprehensive understanding of head impacts in mountain biking. Together, these methodologies and the sensor's code construction contribute to the development of a robust tool for assessing and mitigating the risks associated with subconcussive injuries in extreme sports.

### 4.3. Testing Methodology

A. Accelerometer Drift Test

1. The position of the accelerometer was established and written down on a paper underneath.
2. Turn on the sensor mounted to the helmet and wait ten seconds.
3. After waiting for ten seconds, the helmet was moved along the positive x-axis, then returned to the center and laid stationary for five seconds.
4. The helmet was then moved along the negative x-axis, then returned to the center and laid stationary.
5. Steps 2-4 are repeated for all other axes.
6. Then, hold the helmet stationary in the original center (marked by the paper), wait ten seconds, then turn off the sensor.

B. Gyroscope Drift Test

1. The orientation of the gyroscope was established and written down on a paper underneath it. Two perpendicular lines established with a compass and a ruler are drawn.
2. The gyroscope was turned on and held stationary for ten seconds.
3. Then the sensor was rotated 90 degrees, and rotated back to the initial position, then held stationary for five seconds.
4. This step was then repeated consecutively with 180 degrees, 270 degrees and finally 360 degrees.
5. The sensor was then held for ten seconds stationary, and the sensor was turned off

### 4.4. Methodology for On-Site Testing

The methodology for gathering data with the mountain bike head sensor involved descending down the Cascades trail in Worcester, Massachusetts. Two types of bikes, a Karbon Stampede X0 AXS as our full suspension bike, and a Karbon Powerline 840 GX bike as our hardtail bike, were utilized for data collection. These can be seen in fig 3 and fig 4 respectively.

*Figure 3: Karbon Stampede X0 AXS bike used for full suspension testing, with a front suspension travel of 170mm and a rear suspension travel of 160mm.*

*Figure 4: Karbon Powerline 840 GX bike with 160 mm front suspension travel and 150 mm rear suspension travel was used for hardtail.*

Each bike underwent five runs down the trail, with each run lasting approximately five minutes. Prior to each run, the sensor was turned on to ensure data logging throughout the entire descent. Similarly, after completing each run, the sensor was turned off to delineate independent data sets for each run. This approach ensured that data from each run could be accurately analyzed and compared, providing valuable insights into the forces experienced during mountain biking on several types of bikes.

### 4.5. Data Analysis of Acceleration Data

Once the acceleration was obtained, the sampling frequency of the sensor was 100hz, that means each point of acceleration is separated by 10 milliseconds. Thus, a MATLAB code was written that would read the data sheet composed from the accelerometer, and each point of acceleration was put through the calculation for Head Injury Criterion. This code can be found in appendix B The formula for this calculation is as follows:

$$HIC = \{(t_2 - t_1)[\frac{1}{(t_2 - t_1)}\int_{t_2}^{t_1} a(t)dt]^{2.5}\}$$

Where the acceleration used was the calculation for linear acceleration by taking the acceleration for x, y, z every 10ms and putting them into the formula that follows:

$$a(t) = \sqrt{x^2 + y^2 + z^2}$$

In the HIC formula, $t1$ is equal to the initial point of measurement of the acceleration data, generally at 0 milliseconds, and $t2$ is the time ten milliseconds later. After the HIC was obtained for every point of linear acceleration, the average was taken for the list of HIC generated by the formula of each data sheet. The average HIC was taken for each sheet, then multiplied by the number of seconds of the run. Thus, a table was formed demonstrating these values and can be found in section 5.2.

# 5. Design Verification

The sensor was predominantly tested for proper acceleration measurements, and identification of any potential drift when recording values. Each axis of the accelerometer was tested independently, and the steps for doing so are below. A trail was selected that was short, in order to gain several readings over the same trail and make comparison easier. Once these acceleration results were obtained, they were put through the head injury criterion to quantify them into a tested scale for concussive impacts.

## 5.1. Results

In the results section, we present the findings obtained from extensive data collection efforts during mountain biking trials. Across the multiple runs conducted on the Cascades trail, each data sheet typically comprised approximately 2500-3000 samples, providing a robust dataset for analysis. Acceleration measures ranged between 1-5 meters per second squared, with notable variations observed across different axes. Particularly, the y and z axes exhibited the highest magnitudes of acceleration, indicating significant forces experienced in these directions during the descent. Furthermore, the calculated Head Injury Criterion (HIC) values demonstrated remarkable consistency among each other, highlighting the reliability of our sensor's measurements in assessing potential head injury risks.

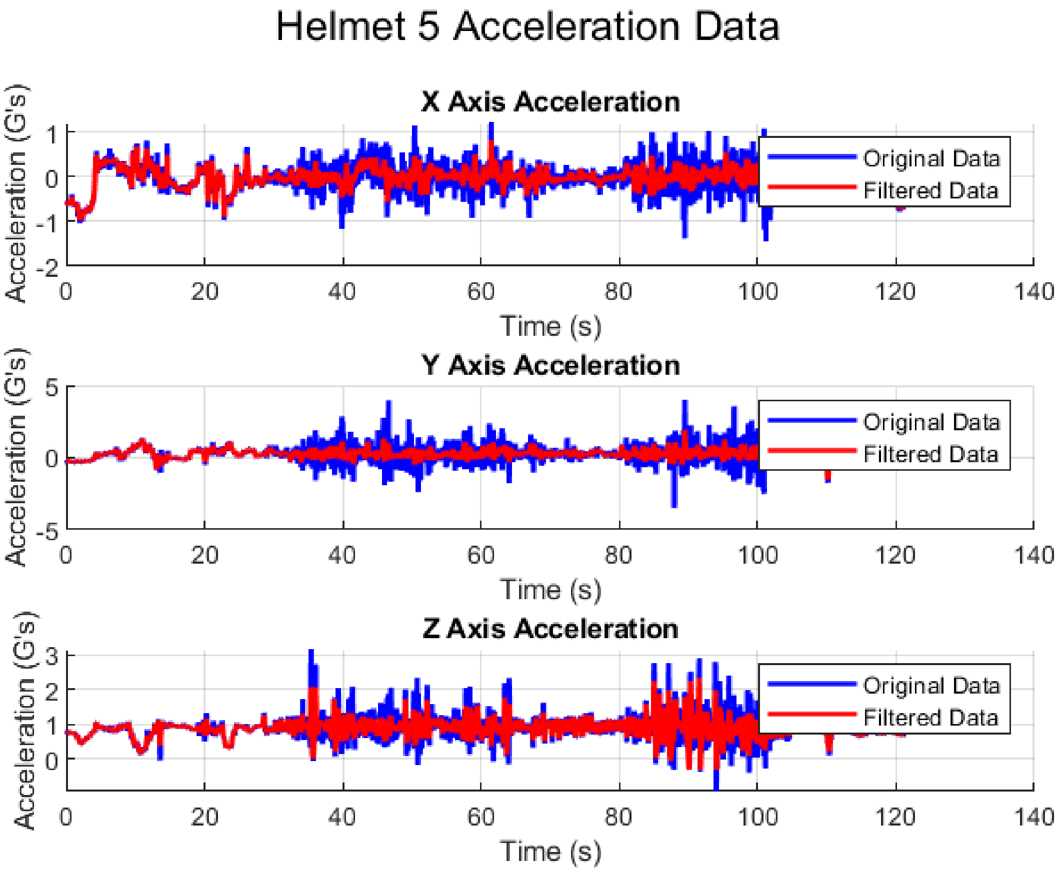


*Figure 5: Filtered and unfiltered linear acceleration data for the Karbon Powerline 840 GX hardtail bike trails.*

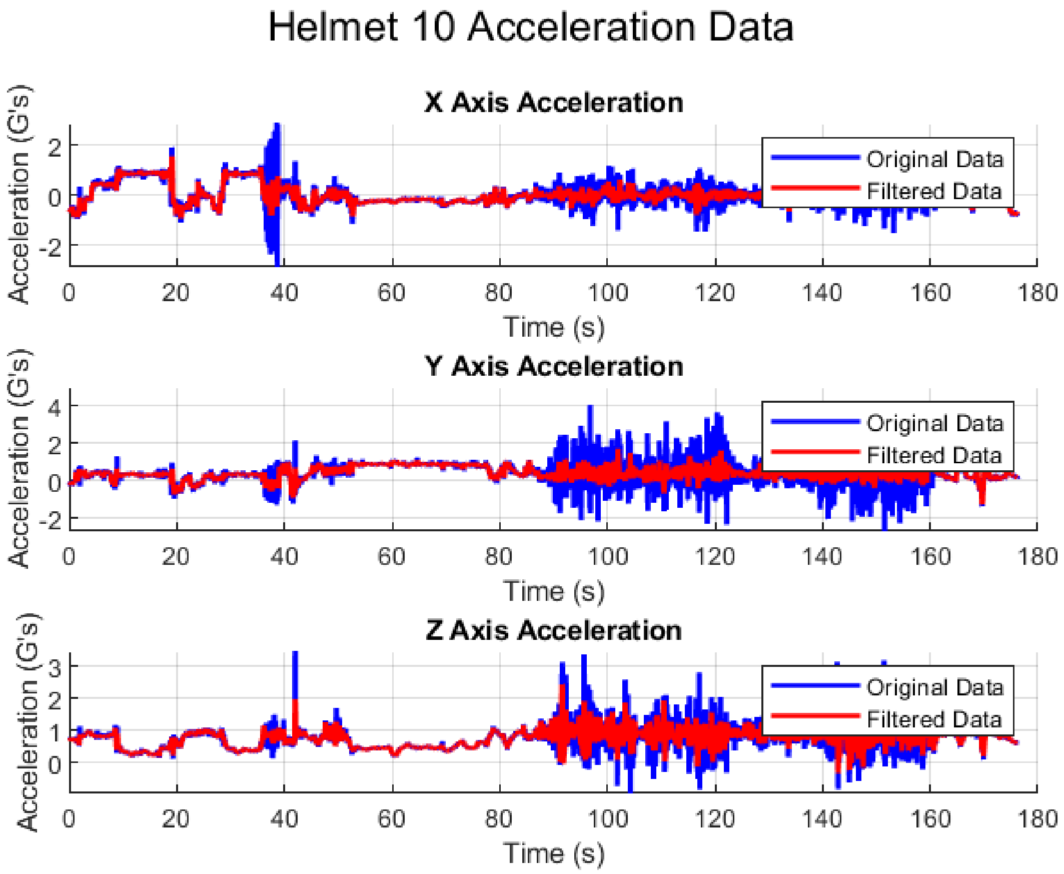


*Figure 6: Filtered and unfiltered linear acceleration data for Karbon Stampede X0 AXS full suspension bike trails.*

### 5.2. HIC Calculation Results

In this section, we delve into the results obtained from our data collection efforts, categorized by the type of bike used during the mountain biking trials. The table presents the total number of data points recorded for each bike type, providing insight into the extent of our data coverage. Additionally, the calculated Head Injury Criterion (HIC) values and Abbreviated Injury Scale (AIS) scores offer valuable information regarding the potential risks associated with head injuries during the rides. Analyzing these results will shed light on the differences in impact severity between hardtail and full suspension bikes, informing future discussions on bike design and rider safety measures.

*Table 2: Suspension type characterized by total number of data points with their total HIC value and their corresponding Abbreviated Injury Scale (AIS)*

| Suspension Type | Total # of data points | HIC | AIS |
|---|---|---|---|
| Hard Tail | 2206 | 204.6408055 | 1 |
| | 2541 | 269.0488319 | 1 |
| | 2558 | 279.9279188 | 1 |
| | 2845 | 346.1352168 | 1 |
| | 4649 | 882.171185 | 2 |
| Full Suspension | 3209 | 441.5474874 | 1 |
| | 2409 | 254.0799997 | 1 |
| | 2132 | 197.8903906 | 1 |
| | 2356 | 248.0444633 | 1 |
| | 1859 | 150.904466 | 1 |

# 6. Validations and Ethics

## 6.1. Validation

Table 3 below contains the previous specifications and whether they were met or not.

*Table 3: Comparison of Specification protocol and confirmation of achievement*

| **Specification** | **Purpose** | **Specification Met?** |
|---|---|---|
| Subconcussive impacts have long term consequences through small mediated but consistent impacts. | Ensures that forces that cause these impacts are minimal yet stacking. | Yes |
| Obtain measurements of magnitude and consistency of forces that impact the head while mountain bike riding. | Clear visualization will allow for easier quantification of damage accumulation | Yes |
| The sensor must have the ability to measure consistently across the entire trail. | Repetition and number of forces can be consistently measured across the entire trail. | Yes |
| An accelerometer connected to an Arduino can measure every force. | Ability to observe and record forces that impact the head every 10 milliseconds. | Yes |
| Number of samples should be consistent for comparison | The same trail will be used over multiple trials, and the Arduino will have capability of stop and starting measurements. | Yes |

| | | |
|---|---|---|
| Forces recorded should have as minimal noise and authentic as possible | Filters will be utilized to remove noise | Yes |

### 6.2. Ethics

In the pursuit of developing a sensor to measure subconcussive impacts in mountain biking, several ethical considerations are paramount. Firstly, the project must address societal influence, ensuring that the production, sales, and marketing of the product are conducted responsibly to minimize any negative societal impacts and promote its beneficial use among ordinary people. Secondly, health and safety issues must be carefully considered to ensure that the product does not pose any risks to the health and personal safety of users, emphasizing the importance of mitigating potential injuries associated with mountain biking. Thirdly, ethical concerns regarding the product's contribution to a good and satisfying life must be addressed, focusing on how the sensor can enhance the well-being and quality of life of cyclists by providing valuable insights into their head impacts and promoting safer biking practices. Lastly, manufacturability plays a crucial role in determining the product's accessibility and scalability, underscoring the need for efficient manufacturing processes to facilitate widespread adoption and long-term sustainability. By incorporating these ethical considerations into the project's development and implementation, it can strive to make a positive impact on both individual cyclists and the broader biking community while upholding ethical standards and promoting responsible innovation.

The results of this project could potentially help establish a new market for lower cost sensors that measure impact trauma. One of the problems found throughout this project was the excessive cost of sensors that are apt for concussive measurements, and thus perhaps this design could help bolster the creation of self-made sensors and influence the availability of subconcussive research.

### 6.2.1. Societal Influence

An ethical consideration for this project involves assessing the societal influence of the developed product, particularly in terms of its impact on "ordinary" individuals. As the project aims to develop a sensor for measuring subconcussive impacts during mountain biking, careful consideration must be given to how the availability and use of this technology may affect the broader community. One potential concern is the normalization and acceptance of subconcussive impacts in extreme sports culture, which could inadvertently downplay the seriousness of head injuries and discourage individuals from seeking appropriate medical attention. Therefore, it is essential to balance the promotion of safety awareness with the enjoyment of the sport, ensuring that the product's marketing and messaging prioritize the well-being of users above all else. Additionally, measures should be implemented to prevent the glorification of risk-taking behaviors and promote responsible riding practices among enthusiasts. By addressing these ethical considerations, the project can strive to have a positive societal influence by promoting a culture of safety and accountability within the mountain biking community.

### 6.2.2. Ethical Concerns

An ethical concern for this project revolves around how the product will contribute to promoting a good and satisfying life for individuals. As the project aims to develop a sensor to measure subconcussive impacts during mountain biking, addressing this concern involves ensuring that the technology enhances the overall biking experience while prioritizing the well-being and satisfaction of cyclists. This includes providing valuable insights into the forces experienced during biking to help riders make informed decisions about their safety equipment and riding practices. Moreover, the sensor should empower cyclists to take proactive measures to mitigate potential risks associated with subconcussive impacts, thereby promoting a safer and more enjoyable biking experience. By prioritizing the enhancement of cyclists' well-being and satisfaction, the project aligns with ethical principles aimed at improving individuals' quality of life.

### 6.2.3. Health and Safety Issues

An ethical consideration for this project pertains to health and safety issues, specifically regarding how the project's outcomes may influence the well-being and personal safety of individuals. Given the focus on developing a sensor to measure subconcussive impacts during mountain biking, it is essential to evaluate how the use of this technology could impact the health and safety of cyclists. Potential risks associated with mountain biking, such as head injuries, concussions, and long-term cognitive health implications, must be carefully considered. Additionally, ensuring that the sensor's implementation does not compromise the safety of cyclists during data collection or distract them from their focus on riding safely is paramount. Striking a balance between innovation and ensuring the protection of individuals' health and safety is crucial in ethical project development.

### 6.2.4. Manufacturability

An important consideration for this project is manufacturability, which pertains to how easily the subject matter of the MQP can be reproduced. The development of a sensor to measure subconcussive impacts during mountain biking demands attention to the feasibility of mass production. This involves evaluating factors such as the availability of materials, the complexity of manufacturing processes, and the scalability of production methods. By ensuring that the sensor design is conducive to efficient and cost-effective manufacturing processes, the project can enhance its potential for widespread adoption and commercialization.

# 7. Impact of Design

## 7.1. Discussion of Results

Once the results were obtained, they were compared to the injury threshold established by the National Highway Traffic Safety Administration (NHTSA) through several years of testing. [2] While the graph was specifically made to refer towards vehicular crashes, with an emphasis on linear acceleration, the results were designed to represent the many slight changes in acceleration as a single significant impact. Then the average was taken from the results to represent 274.94 for the hardtail and 212.73 for the full suspension bike. This sets the level of injury at level 1, which the NHTSA states results in headache or dizziness in the person.

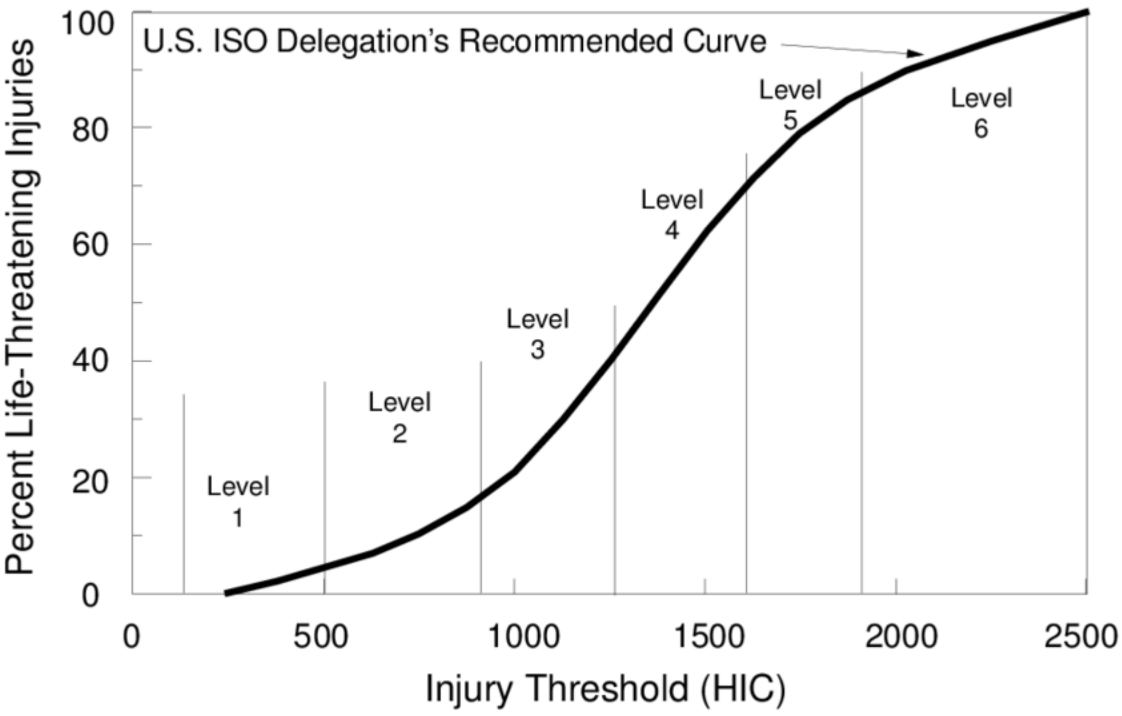
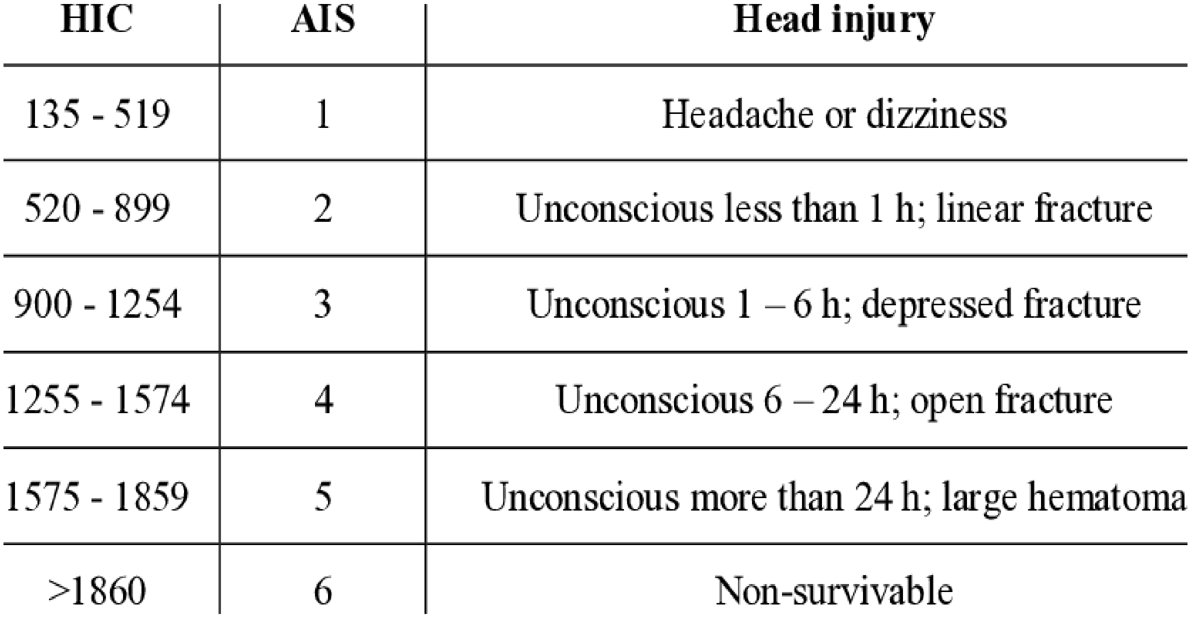


*Figure 7: A graph demonstrating the ISO curve provided by the NHTSA as a scale with the max level being a skull fracture.*

This would be expected and has been a visualized result on mountain bike riders in the past. In 2020, an experiment was conducted to test the visibility of mountain bike riders before and after several different trails. The difference between the two results was described as significant within the study.[1]



| HIC | AIS | Head injury |
|---|---|---|
| 135 - 519 | 1 | Headache or dizziness |
| 520 - 899 | 2 | Unconscious less than 1 h; linear fracture |
| 900 - 1254 | 3 | Unconscious 1 – 6 h; depressed fracture |
| 1255 - 1574 | 4 | Unconscious 6 – 24 h; open fracture |
| 1575 - 1859 | 5 | Unconscious more than 24 h; large hematoma |
| >1860 | 6 | Non-survivable |

*Figure 8: Head Injury Criterion table labeling level of head injury depending on HIC score*

Analyzing the forces experienced on the mountain bike trail and aggregating them into a measurement of Head Injury Criterion (HIC) yields an average HIC indicative of an Abbreviated Injury Scale (AIS) of 1, corresponding to symptoms such as headaches and dizziness. The association between dizziness and headaches and consistent long-term mountain bike riding has been documented in previous studies. Furthermore, research has highlighted the impact of mountain bike riding on vision impairment, a factor often linked with reports of dizziness, particularly in studies detailing the vertigo-like effects of extended mountain bike riding[10].

### 7.2. Sources of Error

Several factors contribute to potential sources of error in the data collected and analyzed in this project. One limitation is the relatively small number of runs conducted on the Cascades trail in Worcester, Massachusetts. The limited sample size may not fully capture the variability in terrain and riding conditions that could influence the forces experienced by mountain bike riders. Additionally, the short duration of the study makes it challenging to assess the long-term effects of mountain biking on subconcussive injuries accurately. Furthermore, since this experiment cannot visualize the brain directly, it is impossible to observe any signs of actual damage. Another limitation is the use of the Head Injury Criterion (HIC) as a metric for assessing injury risk. While HIC provides a standardized measure of head injury severity, it may not fully capture the complexities of subconcussive injuries, especially in the context of mountain biking. Moreover, the placement of the sensor on the top of the helmet may not accurately represent the forces experienced by the brain, as compared to a sensor embedded in a mouthguard, which would provide more direct measurements of head acceleration. These limitations underscore the need for cautious interpretation of the results and highlight areas for future research to address these challenges effectively.

## 8. Conclusion

Overall, there are several limitations with the study of this project that were recognized, but predominantly it is that this sort of study fundamentally requires the long-time observation of several people over the course of their lifetime in mountain bike riding. Yet perhaps there is some credence to the idea that these low-level accelerative forces that impact the head can be categorized as one low level concussion every time one travels downhill on a mountain bike. Since even the HIC scale demonstrates more than anything the probability of there being damage, it is not implausible to say that throughout each trip, long-term damage is a plausibility not a certainty. Overall, it would be interesting to continue this study, and a favorable step in its development would be the creation of a scale, or a way to condense these forces into a unit of measurement that represents differing degrees of subconcussive impact damage. In the end, there is much to suggest that there is risk in performing this activity, even if there are no direct impacts. Thus, the hobby of mountain biking at least deserves closer inspection and more research into its potentially harmful future effects.

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# Appendix A  Arduino Code

```
#include <MKRIMU.h>
#include <SD.h>
#include <SPI.h>

// Pin definitions
const int chipSelect = SDCARD_SS_PIN;
const int buttonPin = 5;
const int greenPin = 4;

// Variables
int buttonState = 0;
int lastButton = 0;
unsigned long currentTime;
File dataFile;
bool recording = false;

// File naming
String prefix = "Helmet";
String type = ".txt";
int n = 0;
String Name = prefix + String(n) + type;

void setup() {
  pinMode(greenPin, OUTPUT);

  // Initialize serial communication
 /* Serial.begin(9600);
  while (!Serial){
    delay(1);}
*/
  // Attempt to initialize the IMU
  if (!IMU.begin()) {
    //Serial.println("Failed to initialize IMU!");
    blinkGreen(); // Blink the green LED
    while (1);
  }

  // Attempt to initialize the SD card
  //Serial.print("Initializing SD card...");
  if (!SD.begin(chipSelect)) {
    //Serial.println("Initialization failed!");
    blinkGreen(); // Blink the green LED
    while (1);
  }
  //Serial.println("Initialization done.");

}

void loop() {
```

```
  float accelX, accelY, accelZ;
  float gyroX, gyroY, gyroZ;
  String dataString;

  // Check if acceleration and gyroscope data are available
  if (IMU.accelerationAvailable() && IMU.gyroscopeAvailable()) {
    IMU.readAcceleration(accelX, accelY, accelZ);
    IMU.readGyroscope(gyroX, gyroY, gyroZ);
    currentTime = millis();
  }

  // Read button state
  buttonState = digitalRead(buttonPin);

  // Check if button is pressed
  if (buttonState == HIGH && lastButton == LOW) {
    // Toggle recording state
    recording = !recording;

    // Toggle green LED based on recording state
    digitalWrite(greenPin, recording ? HIGH : LOW);

    // If recording started, open the file for writing
    if (recording) {
      dataFile = SD.open(getFileName(), FILE_WRITE | O_APPEND);
      if (dataFile) {
        // Write header information to the file
        dataFile.print("Sample Rate = ");
        dataFile.print(IMU.accelerationSampleRate());
        dataFile.println(" Hz");
        dataFile.println("Time\t\tAcceleration in G's\tGyroscope in
degrees/second");
        dataFile.println("ms\t\tX\tY\tZ\tX\tY\tZ");
        //Serial.println("Header Printed");
      }
      //Serial.println("Recording started.");
    } else {
      // If recording stopped, close the file
      dataFile.close();
     //Serial.println("Recording stopped.");
    }
  }

  // Update last button state
  lastButton = buttonState;

  // If recording, write data to the file
  if (recording) {
    dataString = String(currentTime) + "," + String(accelX, 4) + "," +
String(accelY, 4) + "," + String(accelZ, 4) + "," + String(gyroX, 4) + "," +
String(gyroY, 4) + "," + String(gyroZ, 4);
```

```
    dataFile.println(dataString);
  }

  // Delay for stability
  delay(50);
}

// Function to generate unique file name
String getFileName() {
  File root = SD.open("/");
  if (SD.exists(Name)) {
    n++;
    Name = prefix + String(n) + type;
    return Name;
  } else {
    Name = prefix + String(n) + type;
    n++;
    return Name;
  }
  root.close();
}

// Function to blink green LED
void blinkGreen() {
  for (int i = 0; i < 5; i++) {
    digitalWrite(greenPin, HIGH);
    delay(500);
    digitalWrite(greenPin, LOW);
    delay(500);
  }
}
```

# Appendix B  Matlab Code

```
close all;
clear;
clc;
n=5:16;
%% Low Pass Filter
for i = 1:length(n)
   % Construct the filename for the current file number
   fileName = sprintf('HELMET%d.TXT', n(i));
   % Load data from the file
   file_data = importdata(fileName);
   % Extract sample rate
   SR = str2double(file_data.textdata{1}(23-8:20)); % Assuming sample rate is always
at the same position
   % Extract time (adjusted and converted to seconds)
   time = file_data.data(:, 1) / 1000 - file_data.data(1, 1) / 1000;
   % Extract acceleration and gyro data
   acc = file_data.data(:, 2:4);
   gyr = file_data.data(:, 5:7);
   % Store data in struct
   raw_data(i).time = time;
   raw_data(i).acc = acc;
   raw_data(i).gyr = gyr;
   % Accel Data Filters
   % Sample rate (Hz)
   SR = 100;
   % Cutoff frequency (Hz)
   fc = 20;
   % Filter order
   order = 2;
   % Normalized cutoff frequency
   w = fc / (SR / 2);
   % Design the Butterworth low-pass filter
   [b, a] = butter(order, w, 'low');
   % Apply the filter to the accelerometer and gyro data
   filtered_accelx = filtfilt(b, a, acc(:,1));
   filtered_accely = filtfilt(b, a, acc(:,2));
   filtered_accelz = filtfilt(b, a, acc(:,3));
   filtered_rotx = filtfilt(b, a, gyr(:,1));
   filtered_roty = filtfilt(b, a, gyr(:,2));
   filtered_rotz = filtfilt(b, a, gyr(:,3));
   % Plot the original and filtered signals
   figure
   sgtitle(sprintf('Helmet %d Acceleration Data', n(i)));
   subplot(3,1,1);
   hold on
   plot(time, acc(:,1), 'b', 'LineWidth', 1.5);
   plot(time, filtered_accelx, 'r', 'LineWidth', 1.5);
   title("X Axis Acceleration")
   xlabel("Time (s)")
   ylabel("Acceleration (G's)")
   legend('Original Data', 'Filtered Data');
   grid on;
   subplot(3,1,2);
```

```
   hold on
   plot(time, acc(:,2), 'b', 'LineWidth', 1.5);
   plot(time, filtered_accely, 'r', 'LineWidth', 1.5);
   title("Y Axis Acceleration")
   xlabel("Time (s)")
   ylabel("Acceleration (G's)")
   legend('Original Data', 'Filtered Data');
   grid on;
   subplot(3,1,3);
   hold on
   plot(time, acc(:,3), 'b', 'LineWidth', 1.5);
   plot(time, filtered_accelz, 'r', 'LineWidth', 1.5);
   title("Z Axis Acceleration")
   xlabel("Time (s)")
   ylabel("Acceleration (G's)")
   legend('Original Data', 'Filtered Data');
   grid on;
   %HIC Lin
   lin_acc = sqrt(filtered_accelx.^2+filtered_accely.^2+filtered_accelz.^2);
   % Ensure time vector is evenly spaced
   dt = mean(diff(time));
   % Integrate acceleration squared over time
   integral_value = trapz(time, lin_acc.^2);
   % Initialize HIC vector
   HICl = zeros(size(time));
   % Calculate HIC according to NHTSA formula
   for ii = 1:(length(time)-1)
       % Calculate HIC for each time step
       HICl(ii) = (1 / (time(ii+1) - time(ii))) * integral_value * (dt ^ 2.5);
   end
   % Last element of HIC will be zero as there is no next time point to calculate the
difference
   HICl(end) = 0;
  raw_data(i).HIC_Lin = mean(HICl)*time(end);
  % HIC Rot
  rot_acc = sqrt(filtered_rotx.^2+filtered_roty.^2+filtered_rotz.^2);
   % Ensure time vector is evenly spaced
   dt = mean(diff(time));
   % Integrate acceleration squared over time
   integral_value = trapz(time, rot_acc.^2);
   % Initialize HIC vector
   HICr = zeros(size(time));
   % Calculate HIC according to NHTSA formula
   for ii = 1:(length(time)-1)
       % Calculate HIC for each time step
       HICr(ii) = (1 / (time(ii+1) - time(ii))) * integral_value * (dt ^ 2.5);
   end
   % Last element of HIC will be zero as there is no next time point to calculate the
difference
   HICr(end) = 0;
  raw_data(i).HIC_Rot = mean(HICr)*time(end);
end
```