A Dual-Helmet Interpretation of the Virginia Tech STAR Method

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by

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Authorship

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Elizabeth Graveline: Elizabeth was primarily responsible for the development of the background, project statement, and project objectives. She also created a testing procedure including the research of how testing could be conducted and how many tests could be run. She organized team and advisor meetings and served as a primary writer and editor for the final report.

Peter Rakauskas: Peter designed early concepts for the testing rig through computer modeling including parts machined to be used in the final assembly. He selected a set of sensors and code to run them, creating a system to gather data during testing. He also performed the hypothesis testing statistical data analysis, as well as contributing to writing and editing the final report.

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Abstract

Leading helmet testing governing bodies have perfected the kinematics of linear acceleration in a laboratory setting, but research shows that both linear and angular acceleration are present in concussive impacts. Virginia Tech was the first to incorporate both types of acceleration, but their STAR method simulates a generalized version of a concussive impact. Studies show that reproducing specific types of impacts are unique in their respective kinematic motions. The goal of this project was to develop and compare Virginia Tech's STAR testing methodology to a two-helmet version of the test in order to determine if there is a significance in manipulating laboratory helmet tests to specific types of concussive football impacts. The prototype included Virginia Tech's original design with additional parts necessary for reproducing a helmet-to-helmet impact. Due to an inability to test, data analysis was performed on existing VT data and we found that if our linear acceleration data is 37.9 +/- 0.88g's and our angular acceleration is 2036 +/- 37 rad/s^2 from the mean, there is a significant difference in VT's method compared to a helmet-to-helmet method.

Table of Figures

Table of Tables

1.0 Introduction

American football is a popular sport in the United States, with a large fanbase and a considerable number of young people participating. In 2017, 1.06 million high school athletes participated in football (Rapaport, 2018). Of these student-athletes, an estimated 300,000 will suffer concussions, and approximately half of all concussions that occur in football go unreported ("Concussions Facts and Statistics", n.d.). Mild cases of concussion may result in a brief change in mental state or consciousness, while severe cases may result in extended periods of unconsciousness, coma or even death ("Sports-related Head Injury", n.d.). The danger of concussion is not a mystery to those involved in football. Athletes are taught how to recognize the symptoms of head injury in themselves and teammates. Since the desire to play the game is still prevalent among American youth, a challenge arises in reducing the number and severity of head injuries endured by athletes.

The understanding athletes have about the reality of head injury in football is not the issue that needs to be addressed. The problem lies in how players go about protecting themselves, specifically in their choice of helmets. Modern helmets are designed with a reduction of linear force as a priority. These forces are not inconsequential because they cause the brain to hit the inside of the skull upon impact. If the brain impacts the petrous and orbital ridges and parts of the sphenoid, there may be contusions on the brain itself. Large blows to the head and whiplash can cause this kind of brain injury. Football helmet governing bodies are working to correct this by focusing on reducing the traumatic force in the x- and y-planes, but there is more to concussions than big hits. Large and small forces alike can cause rotational forces in brain tissue, especially across lines where tissues of different densities intersect. These forces can damage neurons on the cellular level, making them a danger to athletes (“What happens to the brain during a concussion?”, 1999).

As researchers begin to identify specific forces that cause concussions, helmet testing must continuously grow with the research behind the concussion. Although this seems obvious, helmet testing organizations have yet to perfectly mimic a head-to-head impact in football. Rotational acceleration is accounted for in leading concussion testing protocol from Virginia Tech. However, the National Operating Committee on Standards for Athletic Equipment (NOCSAE) and other committees have helmet testing protocols that only examine linear acceleration. Both of these organizations are the governing bodies behind helmet approval, yet neither has utilized a method that reproduces a helmet-to-helmet impact, a helmet-to-ground impact, and a concussive impact from another part of the body. These different types of impacts are all unique in their respective kinematic motions. Given the fact that a majority of concussions are a result of helmet-to-helmet impacts (Lessley et al., 2018), there needs to be a strong emphasis on effectively testing helmets for this scenario.

2.0 Background

2.1 Concussions in Football

Every year, between 1.6 and 3.8 million sports-related concussions occur in the United States alone, typically as a result from being struck by or against an object (Langlois et al., 2006). Out of every sport in youth athletics, collegiate levels, and professional leagues, football claims the highest incidence of concussion (Daneshvar et al., 2011). It's high-intensity, male-dominated playing field invariably results in injuries at every level of play. An 11-year study reports the incidence of head injury in high school football to be 0.60 injuries per 1000 athlete exposures, which is almost twice as high as the runner-up (Lincoln et al., 2011). At the professional level, studies show that a concussion is reported almost every other game in the National Football League (NFL) (Casson et al., 2010; Daneshvar et al., 2011).

The health problems of current and former players have played a significant role in the increased focus on the issue of concussions over the years. Multiple sources have identified concussion and repetitive subconcussive impacts to be associated with long-term health issues including neurodegeneration (Gavett et al., 2011; Guskiewicz et al., 2005). Former NFL and National Collegiate Athletic Association (NCAA) players have experienced memory loss, behavioral changes, and recurring headaches throughout their careers and beyond.

2.2 Types of Concussive Football Impacts

A video analysis of reported concussive impacts during the NFL's 2015-2016 and 2016-2017 seasons performed by BioCore, LLC, gave a comprehensive overview of the statistics behind concussions (Fig. 1). Across all player positions, 36% of concussions were caused by a helmet-to-helmet impact, 18% by a helmet-to-ground impact, 22% by a helmet-to-shoulder impact, and the remaining 24% by a blow from a region of the body other than the helmet and shoulder (Lessley et al., 2018).

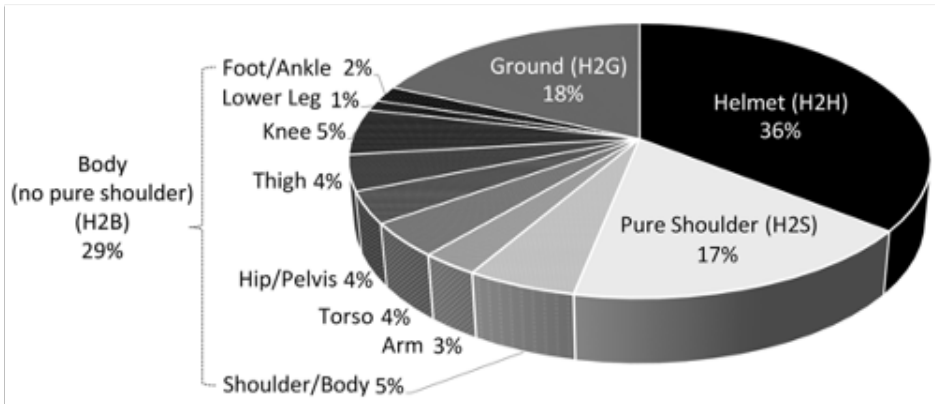

Fig. 1: Distribution of Helmet impact source (Lessley et al., 2018)

The study by Lessley el al. provides three main impacts that cause concussions: helmet-to-helmet, helmet-to-ground, and helmet-to-shoulder. It is important to note that the statistics described above also includes 24% of concussions occurring from impacts to the helmet from a region of the body other than the helmet and shoulder, with helmet-to-knee (5%), helmet-to-thigh (4%), helmet-to-hip (4%), helmet-to-torso (4%), and helmet-to-arm (3%) being the most common of those. Based on the low frequency of these impacts, we will only be focussing on helmet-to-helmet, helmet-to-ground, and helmet-to-shoulder.

2.2.1 Helmet-to-helmet

A helmet-to-helmet impact occurs when one player's helmet contacts another player’s helmet, as depicted in Figure 2.

Fig. 2: Photograph of football helmet-to-helmet impact (Kuo, 2016).

The severity of a helmet-to-helmet impact depends on the rate of change of energy that the head experiences. A study by Withnall et al. (2005) explains that mathematically, a head-to-head impact in football comprises of the product of head mass, acceleration, and velocity plus the product of the head's moment of inertia, angular acceleration, and angular velocity for both the impacted player and the impacting player.

Additionally, a study performed by Viano & Pellman (2005) shows that the primary response of the head is the resultant translational acceleration of the head's center of gravity, with the impact force from the striking player shown in Equation 1 and the impact force equilibrated by the struck player shown in Equation 2.

$$F = m_{\text{Striking}} a_{\text{Striking}} + F_{\text{N}}$$

Eq. 1: Impact force generated by the striking player

$$F = m_{\text{Struck}} a_{\text{Struck}}$$

Eq. 2: Impact force equilibrated by struck player

The study further explains that head acceleration of the striking player is lower than that of the struck player, so the effective mass of the striking player is greater than that of the struck player.

The effective mass of the struck player is shown in Equation 3, with the mass ratio equalling the ratio of head accelerations, shown in Equation 4.

$$m_{\text{Eff.Striking}} = F/a_{\text{Striking}}$$

Eq. 3: Effective mass of the struck player

$$a_{\text{Struck}}/a_{\text{Striking}} = m_{\text{Eff.Striking}}/m_{\text{Struck}}$$

Eq.4: Equation for mass ratio

The mass ratio assumes that a single mass is involved in the head impact for both the striking player and the struck player. Using the above equations, the impact force and other biomechanical responses including head accelerations and changes in velocity describe the mechanics of a helmet-to-helmet collision leading to a concussion in the struck player.

2.2.2 Helmet-to-ground

Helmet-to-ground impacts occur when a player’s helmet contacts the ground, as depicted in Figure 3.

Fig. 3: Photograph of football helmet-to-ground impact (Kite, 2019).

A helmet impact to the ground involves fundamentally different mechanics than a helmet-to-helmet impact in that the impact is to a compliant body (earth) of effectively infinite mass with different interface contact properties than another helmet (Lessley et al., 2018). Pre- and post-impact angular motion of the head plays a significant role in the severity of concussions caused by ground impacts, and the unique aspects of a helmet impacting a rigid, fixed body make these types of impacts ever more dangerous to a player.

Unfortunately and contradictory to helmet-to-helmet impacts, not much can be done by football governing bodies to prevent or minimize helmet-to-ground impacts, as these frequently occur due to the tackling aspect of the game.

2.2.3 Helmet-to-shoulder

Helmet-to-shoulder impacts occur when a player's helmet contacts another player's shoulder and/or shoulder pad, as depicted in Figure 4.

Fig. 4: Photograph of football helmet-to-shoulder impact (Sekulic, n.d.).

Helmet-to-shoulder impacts are the most frequent concussion-causing impact from a part of the body other than the head (Lessley et al., 2018). These impacts are most commonly caused by a player lowering their head and tackling another player, creating a potentially life-threatening force to the striking player's head and neck. The mass of the struck player's body increases the load in the striking player's neck, resulting in neck flexion and lateral bending.

2.3 Helmet Testing

2.3.1 NOCSAE Helmet Standards & Testing Methodology

The National Operating Committee on Standards for Athletic Equipment (NOCSAE) was formed in 1970 to commission research dedicated to injury prevention in sports. NOCSAE is the governing body in charge of creating and regulating standards for all sporting equipment, including football helmets. All football helmet manufacturers must first receive approval from NOCSAE before bringing their helmet to market. In the 1940's and 50's, research began to focus on the improvement of head protection and following the induction of NOCSAE, enforced helmet safety standards were promoted within the NFL and NCAA. Due to these safety regulations in the 1970's, changes were made to the construction and design of head safety equipment including the use of a hard outer shell, as seen in football helmets today. Helmets began to cover and protect fragile portions of the skull that were prone to skull fracture. The safety standards that NOCSAE implemented in the 1970's have not changed drastically over the years.

NOCSAE provides two procedures for testing helmets: a drop test and a pneumatic ram test. In the drop test, a helmet is dropped onto a platform from a specific height, and the velocity in the last 1.5 seconds of free fall along with the deceleration upon impact are used to calculate a severity index. In the pneumatic ram test, the ram provides the impact, rather than gravity.

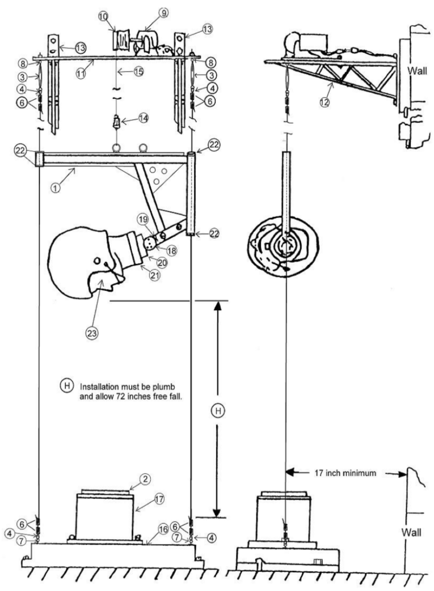

Fig. 5: NOCSAE drop test mechanism

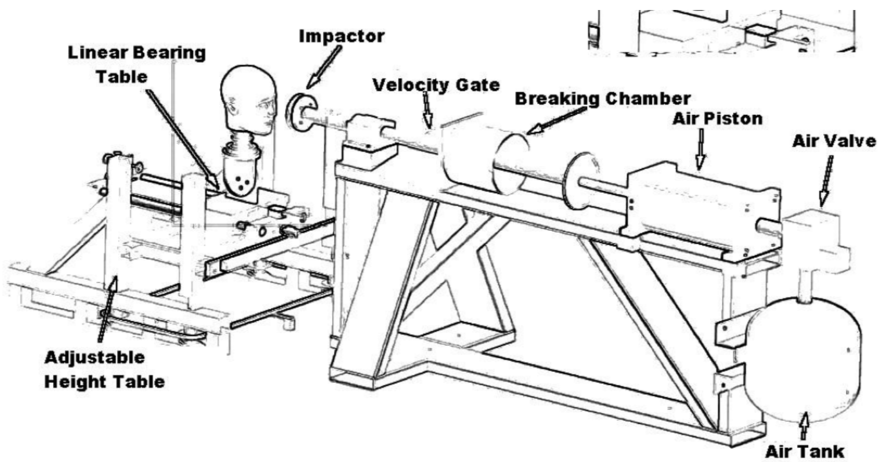

Fig. 6: NOCSAE pneumatic ram testing mechanism

Shown below is the calculation for the Severity Index, where A is instantaneous acceleration upon impact and T is the time interval over which the acceleration impulse occurs.

$$SI = \int_{0}^{T} A^{2.5}\, dt$$

Eq. 5

This equation is used for both the drop test and the pneumatic ram test, with the goal of confirming that a helmet can withstand a specific Severity Index value set by NOCSAE.

Neither the drop test nor the pneumatic ram test are useful in finding out if a helmet can protect the athlete from smaller, repetitive impacts that cause rotational forces within the brain. Their helmet testing methodology only accounts for linear acceleration of the head, whereas linear and rotational acceleration should be considered because they both contribute to concussion risk and are thought to be associated with different injury mechanisms (King et al. 2003; Ommaya, 1984; Unterharnscheidt, 1971). Linear acceleration of the head is associated with a transient intracranial pressure gradient, while rotational acceleration of the head is associated with a strain response (Rowson & Duma, 2013). Because of this, Virginia Polytechnic Institute created a Helmet Lab dedicated to testing a helmet's ability to prevent concussion using both linear and rotational acceleration.

2.3.2 Virginia Polytechnic Institute Helmet Lab & Helmet Testing Method

In 2007, Virginia Tech (VT) created a Helmet Lab under the expertise of Stefan Duma, Professor of Engineering, and Steven Rowson, expert in Biomechanics, with the goal of developing a methodology for helmet testing that simulates on-field impacts by replicating both linear and angular acceleration. Although Virginia Tech has no control over the market approval of helmets, they are the leader in helmet testing. Their Helmet Lab uses a pendulum device to provide impacts to the head. A 15.5 kg impactor is swung into the helmet at four angles, shown in Figure 3. Figure 4 shows the pendulum mechanism as a whole.

Figure 7: Impactor hitting a helmet at Virginia Tech (“Adult football STAR methodology”, n.d.)

Fig. 8: Virginia Tech pendulum testing mechanism (Rowson et al., 2015)

The impactor is swung at the helmet at three different velocities: 3.0, 4.6, and 6.1 m/s. Each test is repeated twice with two different helmets of the same model to ensure thorough testing and accurate data. Helmets are fitted with accelerometers and an angular rate sensor. The data from the sensors is fed into the software with a Butterworth low-pass filter and run through an equation to obtain a Summation of Tests for the Analysis of Risks (STAR) value. The STAR value (Eq. 4) is found by multiplying the predicted on-field exposure (E) at each impact location (L) and velocity (V) by the risk of concussion (R) for that impact using the peak resultant linear acceleration (a) and rotational acceleration (α) from laboratory impacts ("Adult football STAR methodology", n.d.).

$$STAR = \sum_{L=1}^{4} \sum_{V=1}^{3} E(L,V) * R(a,\alpha)$$

Eq. 6

Using the STAR system, Virginia Tech rates helmets using a one to five-star rating, as well as a numerical score. The lower the score, the better the helmet and the more stars the helmet has, the better it is.

2.4 Summary

Virginia Tech has successfully incorporated linear and angular acceleration into helmet testing with the addition of the Model III head and neck on a 5 degree-of-freedom slide table, but the use of a rigid pendulum arm fails to replicate the dynamic motion of a real concussive impact in a game or practice. This mechanism simulates a generalized version of a concussion, whereas reproducing a helmet-to-helmet concussive impact, a helmet-to-ground concussive impact, and helmet-to-shoulder impact are all unique in their respective kinematic motions and might provide differing results when compared to Virginia Tech's current method.

3.0 Methodology

In this chapter, we identify a specific impact to mimic and clearly define our project with a project statement. We then provide objectives and constraints based on the project statement, summarize our project approach, and provide a needs analysis of the components that our prototype must include. Lastly, we identify conceptual design options, discuss final designs of the different prototype components, and describe how we will be testing and analyzing our data from both our prototype and our Virginia Tech prototype.

3.1 Identifying An Impact to Mimic

The team chose to focus on helmet-to-helmet impacts because concussions caused by helmet-to-helmet impacts have the highest incidence rate and have shown to be the most dangerous out of all helmet impacts due to the possibility of two players becoming concussed.

Comparing the current “gold standard” of Virginia Tech’s concussion-replicating helmet testing methodology to an extensive literature review on the kinematics of helmet-to-helmet impacts in consideration with multiple statistics showing that helmet-to-helmet impacts have the highest concussion occurrence, it is clear that incorporating two helmets into Virginia Tech’s pendulum test should be further investigated. A dual-helmet interpretation of the pendulum helmet test might give a more accurate representation of a real-life helmet-to-helmet impact reproduced in a laboratory setting.

3.2 Project Statement

Due to the distinct differences in real-life helmet-to-helmet impacts and Virginia Polytechnic Institute's pendulum helmet testing methodology, the team established the following need statement:

There is a need for a further investigation into the accuracy of the Virginia Tech pendulum helmet testing methodology, specifically in the context of simulating helmet-to-helmet impacts in a laboratory setting.

Following the establishment of a need statement, a project statement was then created to base our design process off of:

Develop and compare Virginia Tech's pendulum testing methodology to a two-helmet version of the pendulum helmet test in order to determine if there is a significance in manipulating laboratory helmet tests to specific types of impacts.

3.3 Objectives

To identify if using two helmets in a pendulum test presents different head acceleration values than the Virginia Tech method of using one helmet, the team developed three core objectives:

1. Create a replica of the Virginia Tech pendulum apparatus and supporting parts including dummy head, neck, tensioning device, and 5 degree-of-freedom slide table.
2. Design and manufacture parts necessary for dual-helmet testing apparatus including a second dummy head, neck, and tensioning device along with a pendulum arm attachment piece.

3. Collect linear and angular head acceleration data from both the VT model and the dual-helmet model.

3.4 Design Process

3.4.1 Needs analysis

In order to create the most effective and efficient testing device possible, a needs analysis was performed. The essential aspects of the final device as well as an explanation for each are included below.

Criteria	Description
Reproducibility & Repeatability of Impacts	The impacts must be reproducible and repeatable in order to generate comparable data.
Generate Linear & Rotational Acceleration	Linear and rotational acceleration must be generated from the impact so as to mimic the forces generated during a concussive impact.
Measurable Linear & Rotational Acceleration	Linear and rotational acceleration must be measurable and comparable.
Mimic Anatomical Movement of Head & Neck	The head and neck must mimic anatomic movement in order to generate data comparable to that of a real football impact.
Accurate Anatomical Measurements of Head & Neck	Anatomic measurements of the head and neck directly correlate to the life-like movements of the head and neck.
Allow Different Locations of the Helmet to be Impacted	The pendulum must be able to impact the helmet at different locations on the helmet.
Apply Above Criteria to Two Helmets	The design requirements stated above must be applicable to the dual-helmet system.

Table 1: Design Criteria

Prior to designing and manufacturing, it is important to rank the importance of the design criteria to establish priorities. Doing this will ease the process of decision-making and guide the team during the design process. This was done through a Pairwise Comparison matrix of our design criteria. *Apply Above Criteria to Two Helmets* is not included in the Pairwise Comparison as it encompasses each of the other criteria within itself and therefore cannot be ranked. The Pairwise Comparison is shown in Appendix A, and the results from the Pairwise Comparison are shown below in Table 2.

Level	Objective	Description
Primary	Reproducibility & Repeatability	The impacts must be reproducible and repeatable in order to generate comparable data.
	Generates Acceleration	Linear and rotational acceleration must be generated from the impact so as to mimic the forces generated during a concussive impact.
	Measurable Acceleration	Linear and rotational acceleration must be measurable and comparable.
Secondary	Mimic Anatomic Measurements	Anatomic measurements of the head and neck directly correlate to the life-like movements of the head and neck.
	Mimic Anatomic Movement	The head and neck must mimic anatomic movement in order to generate data comparable to that of a real football impact.
Tertiary	Impact Different Helmet Locations	The pendulum must be able to impact the helmet at different locations on the helmet.

Table 2: Priority Ranking of Design Criteria

The results of the Pairwise Comparison show that Reproducibility & Repeatability of Impacts, Generate Linear & Rotational Acceleration, and Measurable Linear & Rotational Acceleration are the most important aspects to consider during the design process. Without reproducible and repeatable impacts, our data would not be comparable and therefore would be useless. On a similar note, generating and measuring linear and rotational acceleration is necessary in order to identify if there is a difference between the dual-helmet system and the Virginia Tech system.

Mimicking anatomic movement and measurement proved to be less important. Since the structure of the head and neck will stay constant between the dual-helmet system and the Virginia Tech system, the anthropometric accuracy of the head and neck become less important. In a real testing situation, this criteria becomes much more significant, as it will heavily influence acceleration results and therefore helmet safety results. Allowing different locations of the helmet to be impacted was the least significant design criteria aspect, as it does not directly relate to whether or not there is a difference in linear and angular acceleration using the dual helmet system versus the Virginia Tech system.

3.4.2 Conceptual designs

For clarity purposes, the impactor device is defined as the pendulum and attachment piece and the impactee is defined as the 5 degree-of-freedom slide table, head and neck, and neck tensioning system.

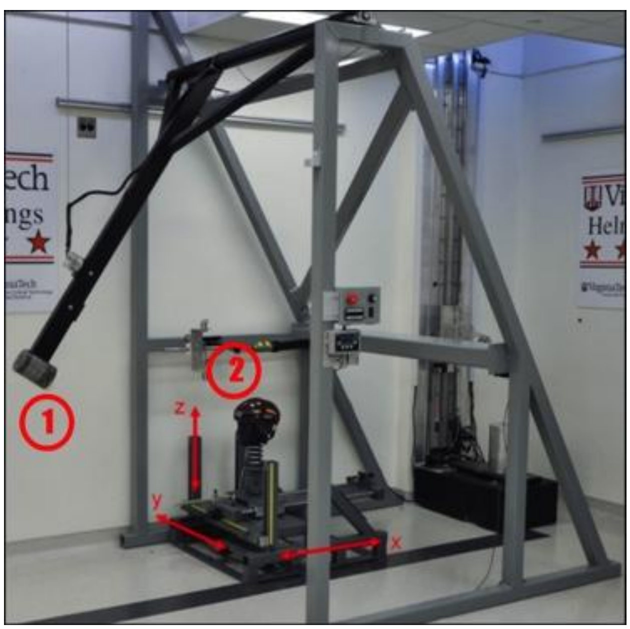

Fig. 9: Visual guide of impactor (1) and impactee (2) (Rowson et al., 2015)

Impactor Device

In order to most accurately recreate Virginia Tech's helmet testing procedure, we will use a pendulum mechanism created by an MQP team from a previous year. This will save us time and resources that we can use to our benefit in other aspects of the final design.

Impactee Device

The impactee device must replicate that of the Virginia Tech model. It must allow for 5 degree-of-freedom motion, including an anthropomorphic head and neck with a distributed weight so as not to hinder natural movement following an impact, and be at a proper height for the impactor to come into contact with the dummy head.

3.5 Final Design

3.5.1 Final design selection

Impactor

A pendulum rig was identified as the best option for the impacting mechanism, since this is what Virginia Tech uses in their methodology. The rig available from a previous MQP consists of two supports on either side of a horizontal crossbar. An arm hangs down from the crossbar and at the bottom end of the arm, there is a removable five-pound impactor. Since this piece is removable, we can easily manipulate it to attach another head to the pendulum arm.

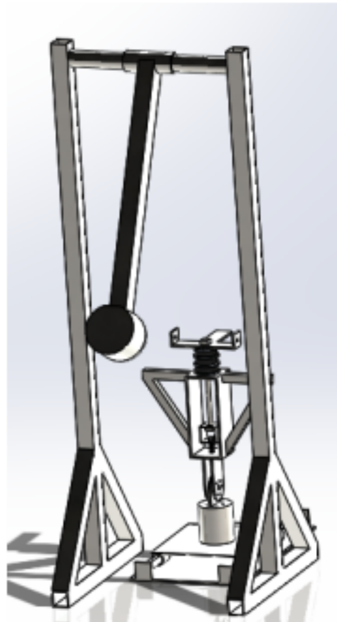

Fig. 10: CAD model of pendulum

Once assembled, we saw that the rig had two separate mounts for the crossbar at two different heights. We then attached the crossbar to the taller setting to accommodate for the height of our slide table.

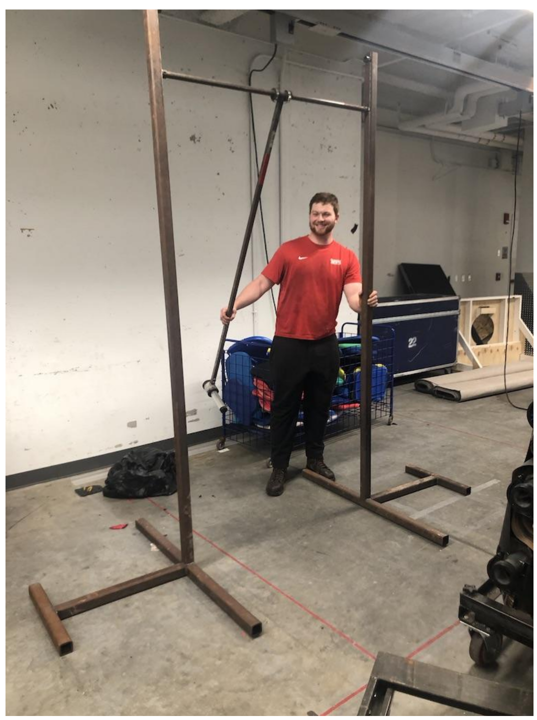

Fig. 11: Assembled pendulum

Impactee

Virginia Tech uses a rail system with 5 degrees of freedom to hold the head that they hit with the pendulum impactor. This allows a full range of motion for the head after it is struck by the impactor.

We designed and constructed a slide table on which to mount our head and neck apparatus as well as the tensioning device. By using a cart with four wheels, we were able to achieve a full range of motion with minimal friction.

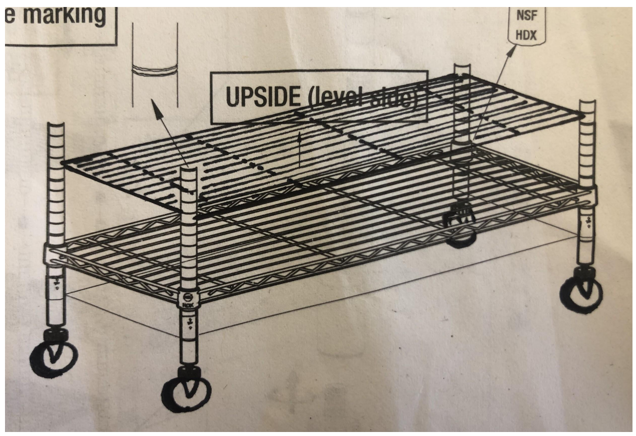

Fig. 12: Slide table design

After considering our options, we settled on purchasing a small set of shelves with pivoting wheels. The other option was to order metal poles, joints, wheels, and mesh screens to be assembled. This option would have resulted in the same product as the shelving but would have taken longer to produce as we would have had to wait for all the parts to be shipped. It would have also been more expensive. We were able to acquire the shelving the same day that we finished the design. The shelving system required some modification to fit our testing procedure. We cut the support poles to prevent them from getting in the way of the impactor. We also inverted the top rack so our tensioning device would pull it in the direction that it was designed to bear weight, making it less likely to move during testing. Figure 13 shows the final design of the slide table with the head and neck and tensioning device attached.

Fig. 13: Assembled slide table

3.5.2 Additional parts necessary for design

Head

Our team utilized a mannequin head that was filled with weight to reach 11 lbs, the average weight of a human head. For the VT method, only one head was needed and for the dual-helmet method, an additional head was manufactured using the same criteria as the first head.

Figure 14: Dummy head wearing helmet

Neck

The neck needs to resemble a human neck for accurate results. It is modeled after the Hybrid III neck used by Virginia Tech. The neck consists of aluminum disks separated by 30 durometer neoprene rubber. A steel cable was tensioned through the center of the neck using a turnbuckle that was attached to the bottom of the slide table.

Figure 15: Hybrid III neck used as a guide for our manufactured neck

Impactor Attachment Piece

Two impactor attachment pieces were needed for testing. The first resembled the impactor that is used by Virginia Tech. It consisted of a circular, rubber disk that acted as the impactor and a cylindrical arm extending from the back. The cylindrical arm was used to weight lift plates in order to increase the impact speed of the pendulum arm. The second attachment arm was used during the two-helmet impacts. It was designed with an anatomically correct neck fixture attached and a connective piece to attach the head/helmet. It also consisted of a cylindrical bar in order to add weight to the pendulum arm.

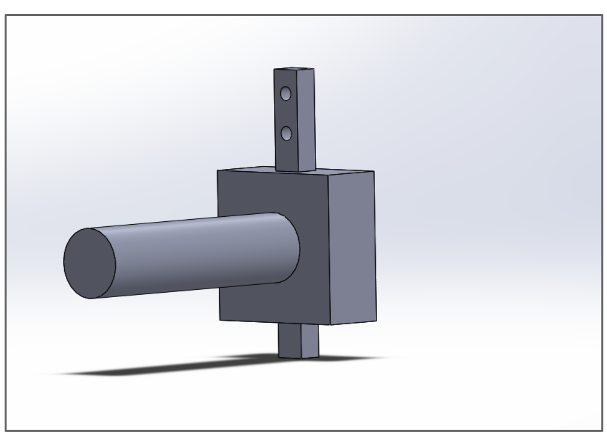

Figure 16: Pendulum attachment piece for dual-helmet impact

3.6 Testing

3.6.1 Data acquisition

To measure the linear and rotational accelerations of the heads within the helmets, we used an Adafruit LSM6DS33 combined accelerometer and gyroscope sensor. This sensor was selected based on a variety of factors. The pinout had to be able to be wired to a microcontroller, which we chose to be Arduino Unos. The sampling rate of the sensor had to be above one kilohertz in order to be able to capture the impact. It also had to be able to measure linear and rotational acceleration while staying within our budget. The Adafruit LSM6DS33 met all of these requirements.

After initial wiring, the sensors were tested using a 1g test per Adafruit's recommendation. The sensors should read 9.8 m/s^2 on each axis if that axis is held vertically. After successfully passing the calibration test, 20 feet of wire was soldered to the sensors so they can be used from a safe distance from the pendulum. One sensor was placed in the mouth of each head. The justification for the placement is based on current industry standards. One of the leading methods for on-field measurement of acceleration is a mouthguard wired with an accelerometer and gyroscope. Putting the accelerometer in the mouth of the dummy head also ensures that the sensor lays flat during testing so all three axes can be reliably measured.

CoolTerm was used to save the serial data from the serial monitor as a text file to the user's computer. This software printed data with timestamps. Knowing the time between readings is important because the sensor outputs m/s^2 and rad/s. In order to calculate rotational acceleration, the rotational velocity will be divided by the time of impact. This setup gives us rotational and linear acceleration, which can be compared between testing methods.

3.6.2 Testing procedure

A specific testing procedure will be followed in order to minimize the risk of injury and maximize testing efficiency. The full version of the testing procedure can be found in Appendix B. A summarization is described below:

1. Place testing helmet on the dummy head with a sensor placed securely in the mouth. Ensure the helmet is positioned so that the helmet will hit the impactor at the desired impact point.
2. Ensure the sensor is recording data and connected to the system.
3. Place the impactee in the correct location underneath the pendulum.
4. Pull the pendulum arm back to the desired height.
5. Give a “3,2,1, dropping call”
6. Release the pendulum arm.
7. Record data.

3.6.3 Safety precautions

Because the pendulum is swinging at a fast rate with concentrated weight at the end, many safety procedures should be followed. All members of the team at the testing site will be required to wear eye protection. A 12 foot by 12 foot perimeter should be marked out around the pendulum and only the operator is allowed within the perimeter. The operator will be required to wear a hard hat while in the perimeter. Before releasing the pendulum arm the operator will give a “3, 2, 1, dropping” call to alert anyone in the room.

3.7 Data Analysis

Once results are gathered through testing, they need to be analyzed. Our original plan was to take data from the helmet-to-helmet trials and compare it to the Virginia Tech style setup. We will use the sample size, mean, and standard deviation from both datasets and run a hypothesis test to see if the results were statistically dissimilar enough to warrant further study in the field of helmet testing. We will set up our null hypothesis to say that there is no significant difference between the two sets of data. Our alternative hypothesis will be that there is a significant difference between the two sets of data. We will select a strong confidence interval of 95%. This means we will be 95% confident that we can reject our null hypothesis before we do so. We will follow the t-statistic formula, seen in Equation 7, to get a t-stat value.

$$\text{t-statistic} = \frac{\bar{x} - \mu_o}{s/\sqrt{n}}$$

Eq. 7: t-statistic Formula

Once we have this value, we can plug it into the T.DIST.2T excel function. This function replaces t tables, which convert a t-stat value to a confidence interval. After subtracting the result from that function from 1 and converting it to a percentage, we will have our final answer. We can then either accept or reject our null hypothesis based on what the test says.

The plan for data analysis was drawn up before school was shut down. After we received news that we would not be allowed on campus, we needed to come up with a plan to analyze data that resembled our original plan as much as possible without actually being able to collect data. Our new plan is to conduct the same hypothesis test, but to work backward using existing data. We will base our results off of a study on linear and angular acceleration measurements used by Virginia Tech in their helmet studies. We will then use the t-statistic formula to create a hypothetical data set for the condition of rejection of the null hypothesis and failure to reject. We will find the mean, sample size, and standard deviation of the original data, and compare it to a data set with a different mean. The mean is what the t-statistic formula allows as a hypothetical variable from the second set of data. The rest of the variables are filled in from the first data set.

After finding this initial data set we will create a table of values that extend in regular increments in the positive and negative directions from the mean of the Virginia Tech sample mean. Then we will enter these incremented values into the t-statistic formula and document at which values we cross our 95% confidence interval. From there we can display data in a graph plotting hypothetical population means against its corresponding confidence interval.

4.0 Results

The results of the statistical comparison showed that even a small variance in mean impact force between helmet to helmet and impactor to helmet provides statistical confidence in a significant difference in the data. The study that we based our values off of has a mean linear impact of 37.9 g, a standard deviation of 10.7 g, and a sample size of 576. The rotational mean is 2036 rad/s^2, a standard deviation of 448 rad/s^2, and the same sample size at 576 samples (Sproule et al. 2017). Using this data set, our t-stat equation was filled out as shown in Equation 8 for the linear data and Equation 9 for the rotational data.

```
=(37.9-38.78)/(10.7/SQRT(576))
```

Equation 8: t-stat Formula With Linear Values

```
=(2036-2036.23)/(448/SQRT(576))
```

Equation 9: t-stat Formula With Rotational Values

The next step was to identify a mean for our hypothetical data to be entered for u in the t-stat formula. U is the variable corresponding to the hypothetical mean. In order to work backward to provide a set of example data that would cause us to reject our null hypothesis and a set that will cause us to fail to reject it, we needed to input a u value that would mean there is 0 confidence in rejection, which would be the sample means. Then we can increase the difference between the sample mean and the hypothesized mean until we reach a 95% confidence interval that the two are significantly different. Because the difference between the sample mean and the hypothesized mean is an absolute value in the t-stat formula, the increase could happen in the positive or negative direction and the result would be the same. The increase was done in increments of .1 in both directions for linear data and 5 for rotational with the corresponding confidence interval recorded with each data point. Once we were near the confidence interval, we increased the number of significant figures and distanced the means by .01 for linear data and .5 for the rotational data.

Hypothetical Values		% Confidence
37.9	37.9	0
38	37.8	17.74
38.1	37.7	34.61
38.2	37.6	49.87
38.3	37.5	63
38.4	37.4	73.75
38.5	37.3	82.11
38.6	37.2	88.31
38.7	37.1	92.67
38.8	37	95.6
38.9	36.9	97.47
39	36.8	98.61
39.1	36.7	99.27
38.75	37.05	94.29
38.76	37.04	94.58
38.77	37.03	94.85
38.78	37.02	95.11

Figure 17: Hypothesized Means and Corresponding Confidence Intervals - Linear

Hypothetical Values		% Confidence
2036	2036	0
2041	2031	21.11
2046	2026	40.76
2051	2021	57.8
2056	2016	71.56
2061	2011	81.9
2066	2006	89.14
2071	2001	93.87
2076	1996	96.75
2071.5	2000.5	94.23
2072	2000	94.57
2072.5	1999.5	94.9
2073	1999	95.21

Figure 18: Hypothesized Means and Corresponding Confidence Intervals - Rotational

From these results, we can conclude that with a difference of only 37.9 +/- 0.88 g and 2036 +/- 37 rad/s^2 we reach a 95% confidence interval. We then represented our findings graphically in Figures 19 and 20.

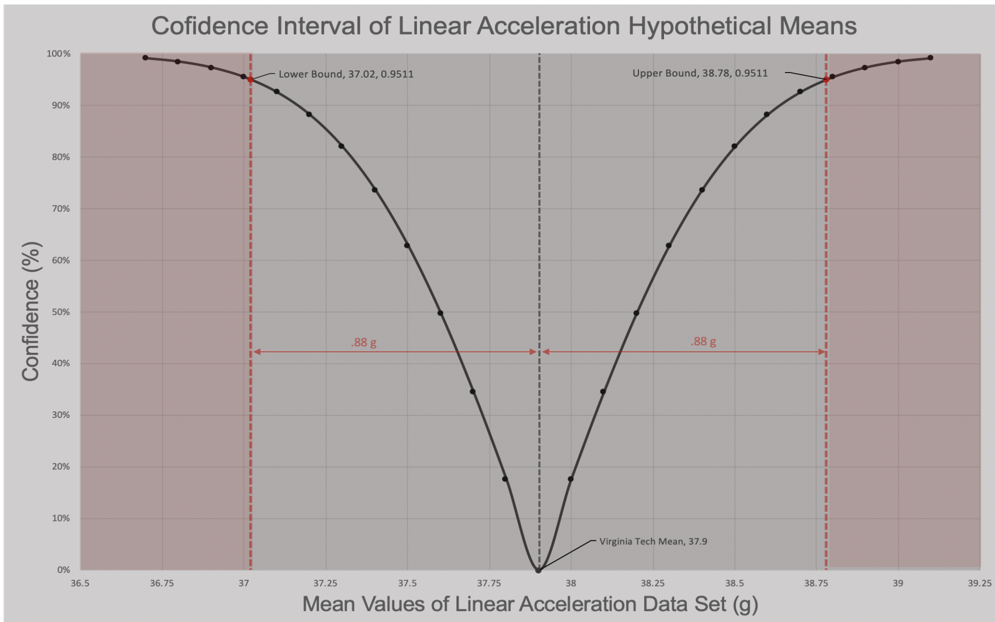

Figure 19: Percent Confidence v.s. Hypothetical Means (Linear)

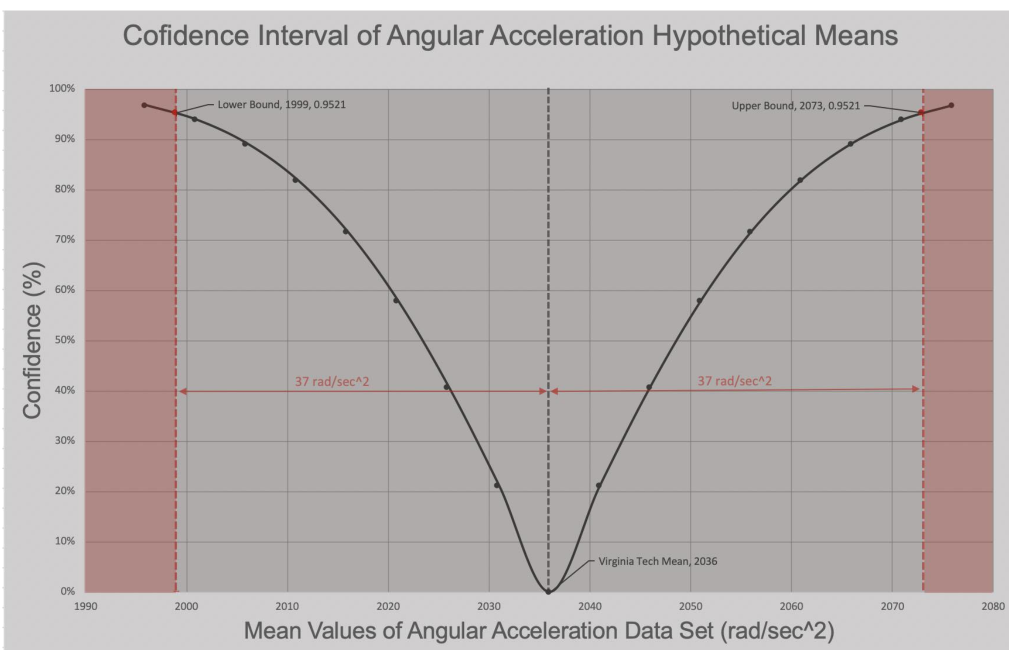

Figure 20: Percent Confidence v.s. Hypothetical Means (Rotational)

5.0 Discussion & Conclusion

After reviewing the literature and current methods in the football helmet testing research space, we saw that helmet to helmet impacts were not tested in a laboratory setting. A rubber impactor made contact with the helmets in all of the leading testing procedures. We noticed that helmet-to-helmet impacts were the most common types of concussive impacts in football so we hypothesized that it would be worth setting up a test rig and protocol that could involve a helmet impactor. To test our hypothesis, we constructed our helmet rig and recreated Virginia Tech's model. We then ran tests with both models and compared the results with the goal of finding out if testing with a second helmet functioning as an impactor would produce differing results from the current industry standard, thereby warranting further study into this area by the industry.

Our findings suggested that there was only a small amount that the means of the Virginia Tech-style results could vary from the dual-helmet results before we were 95% sure of statistical difference. These results prove that our study is valid if these numbers can be reproduced in the helmet-to-helmet test. If there was a large difference between the studies needed to create the 95% confidence interval, the current testing method would still be unquestionably valid. However, since the difference in means is so small it shows that there may be room for professionals in the field to investigate and build off of our study. Due to the school closure, we were never able to gather our own results. This was very disappointing and took away the most important part of our project. We would have liked to see just how different the results between testing styles were, or if they were different at all. Then we would have more conclusive results. Because of our statistics work, we were able to determine that there is a large potential for further investigation into using helmets as impactors in helmet testing.

6.0 Future Recommendations

Our team recommends for future studies to build upon our work in helmet-to-helmet testing and perform physical testing that our team was unable to perform due to the pandemic of 2020. Running physical tests would lead to results that can be used with more conviction than hypothetical statistics. If the tests confirm that there is a significant difference between testing methods, we propose these methods be used across all sporting equipment. We also recommend that future studies investigate helmet to shoulder hits and helmet to ground hits with specialized testing rigs. The current testing of equipment does not create game-like situations that our project set out to investigate so the further investigation into impacts other than a helmet-to-helmet impact would provide a clearer picture of the performance of helmets. Our team recommends that other helmets from sports such as hockey and lacrosse are tested using similar dual helmet testing techniques to simulate game-like hits that the equipment will be put through. Protective sports equipment could be tested in a more specific way that makes playing sports safer for athletes.

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Appendix A: Pairwise Comparison

Objective	Reproducibility & Repeatability	Generate Acceleration	Measurable Acceleration	Mimic Anatomical Movement	Accurate Anatomical Measurements	Impact Different Locations	Total Score
Reproducibility & Repeatability	----------	.5	.5	1	1	1	4
Generate Acceleration	.5	----------	.5	1	1	1	4
Measurable Acceleration	.5	.5	----------	1	1	1	4
Mimic Anatomical Movement	0	0	0	----------	.5	1	1.5
Accurate Anatomical Measurements	0	0	0	.5	----------	1	1.5
Impact Different Locations	0	0	0	0	0	----------	0

Appendix B: Testing Procedure

SETTING UP (FIRST TIME):

1. All Team Members retrieve pendulum device, ladder, impactor, and head/neck apparatus from Sports and Recreation Center Loading Dock; bring items into Sports and Recreation Center Robotics Pit.
2. Team Members 1 and 2 measure a 12ft by 12ft area free from any objects or walls and out of direct pathway of doors/closets in Robotics Pit; mark area with tape.
3. Team Members 3 and 4 set up computers for accelerometer, test accelerometer to make sure data is being sent to computers; place computers outside of 12x12ft area.
4. All Team Members assemble pendulum device in center of 12x12ft area.
5. Team Members 1 and 2 confirm placement of pendulum by measuring distance from center of pendulum to taped perimeter, assuring tape measure reads 6ft +/- 4in.; repeat for 2 sides of perimeter.
6. Team Member 1 tape an "X" on the ground in the center of pendulum device; write "pendulum" in permanent marker on tape.
7. Team Members 3 and 4 attach head/neck apparatus to pendulum arm.
8. Team Members 2, 3, and 4 place impactor in appropriate spot based on location in which markers on both helmets contact one another.
9. Team Member 1 tape an "X" on the ground in center of impactor device; write "impactor" in permanent marker on tape.
10. Team Members 1 and 2 exit 12x12ft area; Team Members 3 and 4 retrieve ladder and place on the back side of the pendulum.
11. Team Member 3 climb ladder; Team Member 4 hand Team Member 3 pendulum arm to test arm height relative to ladder position. To ensure safety, Team Member 3 and 4 always face one another, never have backs turned on pendulum arm.
12. Adjust ladder placement: Team Member 3 gently hand pendulum arm back to Team Member 4; Team Member 4 bring pendulum arm back to resting position (vertical arm); Team Member 3 get down from ladder, move ladder position; repeat process until ladder is in position that allows adequate pendulum arm height.
13. Team Member 1 tape an "X" on the ground in center of ladder; write "ladder" in permanent marker on tape.

SETTING UP (NOT FIRST TIME):

1. All Team Members retrieve pendulum device, ladder, impactor, and head/neck apparatus from Sports and Recreation Center Loading Dock; bring items into Sports and Recreation Center Robotics Pit.
2. All Team Members identify any objects within 12x12ft perimeter; move to outside of perimeter.
3. Team Members 3 and 4 set up computers for accelerometer, test accelerometer to make sure data is being sent to computers; place computers outside of 12x12ft area.
4. All Team Members assemble pendulum in center of taped "X" labeled "pendulum".

5. Team Members 1 and 2 confirm placement of pendulum by measuring distance from center of pendulum to taped perimeter, assuring tape measure reads 6ft +/- 4in.; repeat for 2 sides of perimeter.
    a. If tape measure does not read 6ft +/- 4in., repeat #2 and #5 in SETTING UP (FIRST TIME).
6. Team Members 3 and 4 attach head/neck apparatus to pendulum arm.
7. Team Members 2, 3, and 4 place impactor in center of taped "X" labeled "impactor"; confirm markers on both helmets contact one another.
    a. If tape "X" is not in the center of impactor, repeat steps #8 and #9 in SETTING UP (FIRST TIME).
8. Team Members 1 and 2 exit 12x12ft area; Team Members 3 and 4 retrieve ladder and place over center of taped "X" labeled "ladder"; confirm adequate ladder position by repeating #10 in SETTING UP (FIRST TIME).
    a. If ladder is not in correct location, repeat #12 and #13 in SETTING UP (FIRST TIME).

TESTING:

1. Team Members 1, 2, and 3 exit 12x12ft area; Team Member 4 climb ladder with pendulum arm.
    a. Team Members 1 and 2 man computer programs for accelerometer;
    b. Team Member 3 spot Team Member 4 from outside of 12x12ft area.
2. Team Members 1 and 2 prepare computers for test; call out "computers ready" when computers are prepared for drop.
3. Team Member 4 give "dropping in 3, 2, 1" call; drop pendulum arm.
4. Team Member 4 wait until pendulum arm and impactor stop moving, get down from ladder.
5. Team Member 3 and 4 analyze physical components, look for any deformation;
    a. If no deformation is present, repeat #7 in SETTING UP (NOT FIRST TIME) for each marker location.
6. Team Member 3 exit 12x12ft area.
7. Repeat steps 1 through 6 until testing is completed.

BREAKING DOWN

1. Remove impactor, head/neck apparatus, and ladder from Sports and Recreation Center Robotics Pit; bring items into Sports and Recreation Center Loading Dock.
2. Break down pendulum; bring into Loading Dock.
3. Put away computers, any other objects used for testing.