# Quantifying the Characteristics of Real-World Bicycle Helmet Impacts

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ACADEMIC ABSTRACT

Cycling is an increasingly popular mode of transportation and a preferred form of exercise worldwide. From 1990 to 2015, commuting via bicycle increased as much as four-fold in cities across North America and Europe. However, this increase in cycling is associated with an increase in cycling related fatalities and head injuries. The best way to prevent severe head injury while cycling is to wear a bike helmet. Bike helmets are designed to decrease the linear acceleration of the head, decreasing the rider's risk of severe head injuries, such as skull fracture. In order to sell a bike helmet, it must meet a minimum standard of protection based on linear acceleration of the head upon impact. However, bike helmet impacts are not completely linear in nature and experience a tangential component through angled impacts of the helmet, resulting in rotational accelerations and shear-strain at the skull-brain interface. This strain cause brain injuries such as concussion. Therefore, recent helmet advancements have aimed to decrease rotational acceleration of the head. To continue the advancement of helmet technology and the subsequent decrease of brain injury risk to riders, investigating the impact conditions of real-world impacts is pertinent. This thesis aimed to increase the current body of knowledge of cycling related head impacts. The first aim was to quantify real-world impact locations and analyze how impact location may influence helmet performance. The second aim of this thesis was to investigate the impact velocities and resulting kinematics of real-world crashes based on the magnitude of corresponding damage conditions. Additionally, this aim analyzed the impact conditions from cases which resulted in concussion. Together these studies aim to provide valuable real-world data to be used for the advancement of helmet technologies and design.

# Quantifying the Characteristics of Real-World Bicycle Helmet Impacts

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GENERAL AUDIENCE ABSTRACT

Cycling is an increasingly popular mode of transportation and a preferred form of exercise worldwide. From 1990 to 2015, commuting via bicycle increased as much as four-fold in cities across North America and Europe. However, this increase in cycling is associated with an increase in cycling related fatalities and head injuries. The best way to prevent severe head injury while cycling is to wear a bike helmet. Bike helmets are designed to decrease the linear acceleration of the head, decreasing the rider's risk of severe head injuries, such as skull fracture. In order to sell a bike helmet, it must meet a minimum standard of protection based on linear acceleration of the head upon impact. However, bike helmet impacts are not completely linear in nature and experience a tangential component through angled impacts of the helmet, resulting in rotational accelerations and shear-strain at the skull-brain interface. This strain cause brain injuries such as concussion. Therefore, recent helmet advancements have aimed to decrease rotational acceleration of the head. To continue the advancement of helmet technology and the subsequent decrease of brain injury risk to riders, investigating the impact conditions of real-world impacts is pertinent. This thesis aimed to increase the current body of knowledge of cycling related head impacts. The first aim was to quantify real-world impact locations and analyze how impact location may influence helmet performance. The second aim of this thesis was to investigate the impact velocities and resulting kinematics of real-world crashes based on the magnitude of corresponding damage conditions. Additionally, this aim analyzed the impact conditions from cases which resulted in concussion. Together these studies aim to provide valuable real-world data to be used for the advancement of helmet technologies and design.

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# INTRODUCTION

Cycling is a popular form of exercise and mode of transportation in North America and Europe.[1,2] Cycling is commonly used as a replacement to cars to avoid increasing emissions or to improve cardiovascular health. However, cycling doesn't come without risks. According to the Center for Disease Control and Prevention (CDC), there were 467,000 bike accidents in the United States in 2015, over 1,000 having been fatal.[3] To further increase the popularity of cycling, without further increasing the risk of injury, measures to make cycling safer are necessary.

Bike helmets are the best way to avoid fatalities and protect the skull and brain against injury.[4-10] Skull fracture is highly associated with linear impacts which exceed an individual's threshold for injury.[11] To decrease the risk of skull fracture, bike helmets utilize expanded polystyrene (EPS) foam which deforms upon impact. This increases the duration of the impact and increases the surface area over which the impact occurs, reducing the risk of brain injury. To be sold on the market in the United States, bike helmets cannot allow the headform to exceed a linear acceleration of 300 g,[12] a level associated with 50% risk of skull fracture.[13]

However, traumatic brain injuries, such as concussion, are associated with linear and rotational accelerations. Rotational accelerations of the head are associated with shear strain at the skull-brain interface, which leads to diffuse brain injuries, such as diffuse axonal injuries and concussion.[14,15] While decreasing linear acceleration is a contributing factor to decreasing the risk of concussion, it does not address both sides of the story.

One method used to improve bike helmets ability to reduce rotational acceleration of the head is with helmet testing which include oblique impacts. Evaluating a helmet's ability to mitigate rotational motion gives helmet manufacturers an incentive to continue improving helmets in linear and rotational motion. There are multiple third-party laboratories testing helmets which are separate entities from the governing bodies which set helmet standards. These testing protocols are not required to sell a helmet on the market, but give consumers additional information on helmet performance. [16-18] Testing helmets on oblique anvils is an improvement in realistic helmet evaluations, however, there is little real-world data to inform these test methods.

The objective of this thesis is to quantify the impact characteristics of real-world bike crashes. The first aim of this thesis is to quantify impact locations and present how helmets perform at these locations under CPSC testing protocols. The second aim of this thesis is to estimate the impact kinematics and velocities for bike helmets from real-world impacts, some which resulted in concussion. This data can inform helmet testing procedures, as well as, inform researchers about injury mechanisms and the corresponding impact conditions.

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CHAPTER 1

# The Range of Bicycle Helmet Performance at Real World Impact Locations


## Abstract

To sell a bike helmet in the United States, it must meet standards set by the Consumer Protection and Safety Commission (CPSC). Bike helmets are only required to be tested above an established test line. Unregulated helmet performance below the test line could poses an increased risk of head injury to riders. This study quantified the impact locations of damaged bike helmets from real-world accidents and tested the most commonly impacted locations under CPSC bike helmet testing protocol. 95 real-world impact locations were quantified. The most common impact locations based on azimuth and elevation were side-middle (31.6%), rear boss-rim (13.7%), front boss-rim (9.5%), front boss-middle (9.5%), and rear boss-middle (9.5%). The side-middle, rear boss-rim, and front boss (front boss-middle and front boss-rim regions combined) were used for testing. The rear boss-middle was not used due to a more commonly impacted region in the same azimuth bin. Two of the most commonly impacted regions were below the test line (front boss-rim and rear boss-rim). 12 new helmet models were tested under CPSC protocol at three locations each for a total of 36 impacts. An ANOVA test showed that impact location had a strong influence on the variance of PLA ($p = 0.002$). A Tukey HSD determined that the side-middle (214.9 g ± 20.8 g) and front boss (228.0 g ± 39.6 g) locations were significantly higher than the rear boss-rim (191.5 g ± 24.2 g). The highest recorded PLA (318.84 g) was at the front boss-rim region. This was the only test that exceeded the 300 g threshold. This study presented a method for quantifying real-world impact locations of damaged bike helmets. Higher variance in helmet performance was found at the regions on or below the test line than in the region above the test line.

## INTRODUCTION

Cycling is an increasingly popular mode of transportation [1] and a preferred form of exercise worldwide.[2] From 1990 to 2015, commuting via bicycle increased as much as four-fold in cities across North America and Europe.[1] However, this increase in cycling is associated with an increase in cycling related fatalities and head injuries. From 1998 to 2013, head injuries increased by 60% in hospitalization cases.[3] In 2018, cycling related fatalities in the United States were the highest since 1990 (859 fatalities).[4] Head injuries have a significant impact on fatality occurrence in hospitalization cases.[5] Bike helmets are the most effective method in reducing the risk of head injury.[6-10]

Many countries have developed standards to regulate the construction, labeling, testing, and performance of bicycle helmets sold within their jurisdiction. Most standards require that the minimum function of a helmet is to absorb impact energy and provide a retention system to the wearer's head. The details of each standard vary between governing bodies. The Consumer Product Safety Commission (CPSC) states that any bicycle helmet sold in the United States cannot exceed a peak linear acceleration (PLA) of 300 g (> 50% risk of skull fracture or severe brain injury)[11] during testing.[12] Whereas, standards in Europe (EN) and Australia/New Zealand (AS/NZS) use 250 g as the impact attenuation threshold for failure. All of these standards designate a test line, below which, helmets are not required to be tested. The test line determined by the CPSC lies more than 25 mm above the rim of the helmet. However, multiple studies which have analyzed impact locations in bike helmets have found the rim to be a commonly impacted helmet region.[13-16] Without requiring impact testing below the test line, unknown performance variability likely exists at these common impact locations. Previous studies have analyzed impact attenuation at impact locations on and below the helmet rim. In some cases, helmets exceeded a PLA of 300 g when tested on or below the test line.[17,18]

Unknown variability in any helmet region allows for possible disparities in rider protection. In the past, bike helmet impact locations have been measured using computational simulation methods or by qualifying the impact into a pre-defined bin on a headform. Computational simulations give precise damage metrics and impact kinematics, but are limited by the number of simulations and lack of real-world data to validate the models. Qualitative indications of impact locations are helpful to determine common impact regions, but lack the ability to analyze the data points individually across the whole head. A quantitative method to establish impact locations provides precise data points and gives the ability to analyze spread of the individual impact locations. The objective of this study was to develop a method for quantifying impact location on bike helmets damaged in real-world accidents and analyze bike helmet performance at the most commonly impacted locations.

## METHODS

Damaged bicycle helmets were donated from a manufacturer through a helmet warranty program. Prior to quantifying impact location, we had to mark the point on each helmet where we believed the primary impact occurred. This process was up to the discretion of the researcher and therefore not entirely objective. However, there were guidelines to in place to ensure that each helmet was inspected thoroughly and the primary region of damage was marked to the best of our ability without quantifying the damage characteristics. We inspected each helmet to identify the primary damage region. The primary damage region was characterized by a region of damage with the most severe scrape along the outer liner, crushing of the expanded polystyrene (EPS) foam, or a combination of both factors. It was within this region that the precise impact location would be marked. A majority of the helmets had one large, homogeneous impact region which was easily identified as the primary impact region. In these cases, the center of the surface area encompassing the damage was marked as the precise impact location. If there was a focal point of extreme crush within the primary damage region which was not in the center of the damage region, it was marked as the impact location due to the high concentration of force necessary to create a focal impact. If there were two impact locations on the helmet, the location with more severe crush and scraping was chosen as the primary impact location. If there were several small, focal impacts in one area of the helmet, the impact location was marked at the center of this region.

There were two cases which presented long scrapes, extreme crush, and the liner torn in multiple places on almost the entire left or right side of the helmet. However, these cases were most likely caused by multiple repeated impacts. To address these cases, the subregion which presented the most severe crush was identified and the center of this subregion was marked as the impact location. Although this was a subjective process, most of the helmets we evaluated had an obvious primary impact region and the precise impact location was marked at the center of that region. If there was not visible damage to determine a primary damage region, the helmet was excluded from the study.

**Quantifying Impact Location**

Once all helmets were marked with the impact location, each helmet was properly fit onto a National Operating Committee for Standards of Athletics Equipment (NOCSAE) headform according to the prescribed helmet fit instructions found on the manufacturer's website. Small, medium, and large NOCSAE headforms were used depending on the corresponding helmet size. Each headform was attached to an appropriately sized Hybrid III neck. A custom adaptor plate was used to mate the headform and neck.19 The NOCSAE headform was used because the position of the basic planes marked on the headform surface relative to the center of gravity (CG) of the headform were known. Additionally, the NOCSAE headform has a fully-featured face and realistic head shape,20 which aided fitting each helmet. After each helmet was fit to the headform, a laser was pointed normal to the helmet shell at the impact location. The laser was mounted on a tripod to stabilize and fix its position. The helmet was removed so the laser projected the same vector on the headform surface. This point was marked directly on the headform.

The headform and camera were both mounted a fixed distance apart so that every photo was taken from a set distance. Two photos were taken of the headform, one in the coronal plane and one in the sagittal plane. Each plane could be photographed in two directions: front or back in the coronal plane and left or right in the sagittal plane. The orientation chosen was determined by the quadrant in which the impact location was located. In each photo, the pixel space was calibrated using a ruler held in the same plane as the impact location, parallel to the camera lens. If the marked point was not visible due to the curvature of the headform, a small perturbation was placed on the headform at the impact location.

In each photo, the impact location, intersection of basic planes and one inch on the ruler were marked. MATLAB (Mathworks Inc., Natick, MA). was used to establish a 2D coordinate system in each photo in the horizontal and vertical directions. The known distance between the intersection of the basic planes and the CG was used to translate the basic planes intersection coordinates to the estimated CG coordinates. These measurements were different for each NOCSAE headform size and were adjusted accordingly. The coronal view was used to measure the y distance from the impact location to the CG and the sagittal view was used to calculate the x and z distances. Once the distance from the CG to the impact location was calculated in the x, y, and z directions a 3D coordinate system was established.

Azimuth (θ) and elevation (ρ) were used to characterize the impact location. Azimuth was defined as the angle in the transverse plane relative to the sagittal plane at the front of the headform. Azimuth values on the right side of the headform were positive, and values on the left were negative. However, the absolute value of each azimuth was used for analyses, given the head's symmetry about the mid-sagittal plane. Elevation was defined as the angle relative to the transverse plane defining the height of impact. The rim was defined as an elevation below 30º. This threshold represents the test line for the sake of this study. The location of each damage point was categorized into bins to define general testing regions.

**Drop Tests**

Twelve different bicycle helmet models were purchased for performance evaluation. These helmet models were easily accessible from national brand stores and ranged in price from $20 to $60 and represented a range of popular helmet brands. All helmet models were purchased in a size medium to properly fit a magnesium ISO headform (size J). A twin-wire drop tower and a flat steel anvil were used in each test. Each helmet was impacted at a velocity of 6.2 m/s, the standard CPSC testing velocity for high-speed, flat impacts. The impact velocity was measured using a photogate (BeeSpi V, NaRiKa Corp., Tokyo, Japan). Impact velocity was measured within 40 mm of helmet-to-anvil contact to comply with CPSC standards. Each helmet model was tested once at the three most common impact locations (side-middle, rear boss-rim and front boss) resulting in 36 total impacts. Each impact center was placed at least 120 mm apart from the other two to avoid overlapping damage profiles.12 All visors were removed before testing, as they have been shown to have an insignificant effect on impact attenuation.17 Linear acceleration of each impact was measured using a single-axis accelerometer (Endevco 7264B-2000, Meggitt Orange County, Irvine, CA) placed at the headform CG. Each impact location was verified to match the corresponding bin using the damage quantification procedure described previously.

**Data Analysis**

The drop test data were filtered using a four-pole phaseless Butterworth lowpass filter with a cutoff frequency of 1650 Hz and a CFC of 1000 in accordance with CPSC (SAE J211) specifications.12 A mixed model analysis of variance (ANOVA) was used to analyze the effects of helmet model and impact location on PLA. A Box-Cox transformation was applied to PLA to meet the assumption of constant variance. Tukey's honestly significant difference (HSD) post-hoc test was used to compare PLA between locations. The risk of brain injury was calculated based on the average PLA at each location. Average differences in PLA 95% confidence intervals are also reported to give an estimate of effect size for these comparisons. All statistical tests reference a significance level of $\alpha = .05$ (JMP Pro 11, SAS Institute Inc., Cary, NC). The coefficient of variance (COV) was calculated at each location to determine intra-location variance.

**RESULTS**

Of the 99 damaged helmets donated, 95 had detectable impact regions. The overall average azimuth was 95.1º ± 46.0º, and the average elevation was 36.6º ± 14.1º (Figure 1).

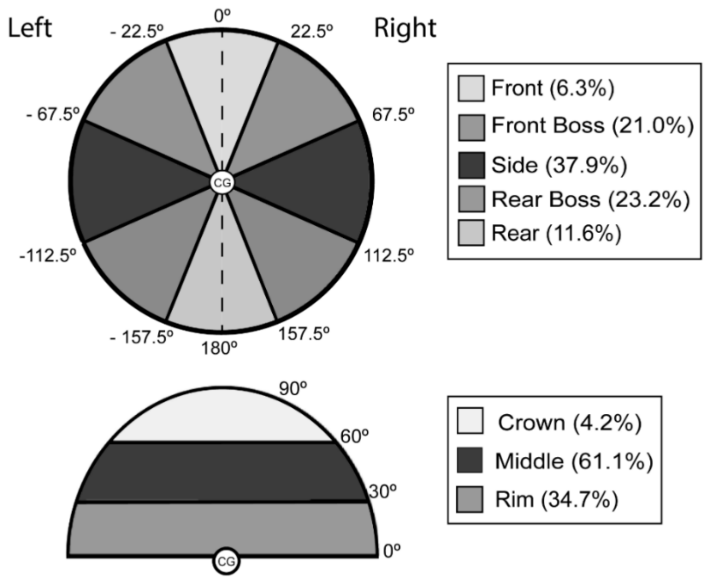


**Figure 1.1.** Impact regions and their respective impact density. Bin shading is proportional to impact density.

The most commonly impacted azimuth regions were side (37.9%), rear-boss (23.2%), and front-boss (21.1%). The most commonly impacted elevation regions were middle (61.1%) and rim (34.7%) (Figure 2).

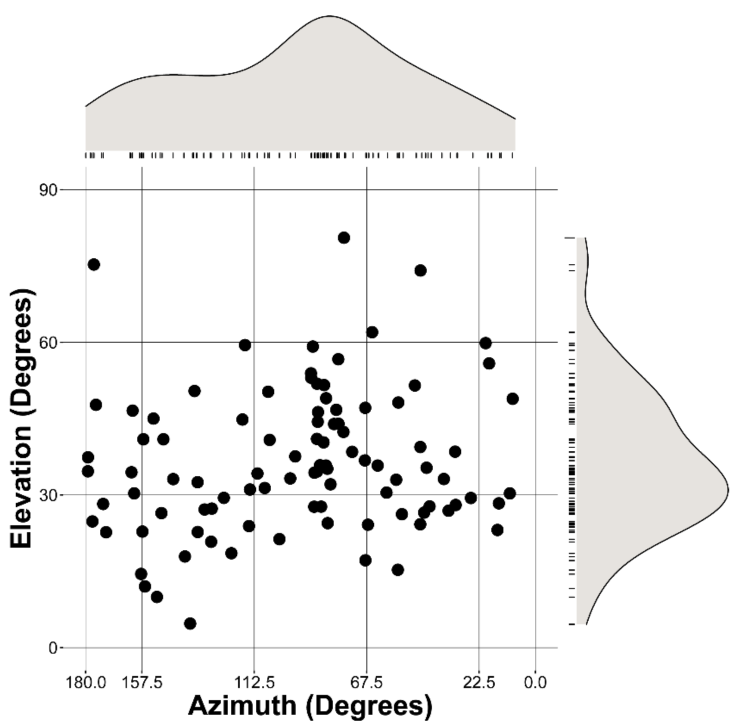


**Figure 1.2.** Discrete and continuous plots of azimuth and elevation values from real-world bike helmet impact locations. Azimuth was more closely centered around the midsagittal plane (SKP = .131) whereas, elevation had a higher density near the helmet rim (SKP = .613). Each tick mark below the density plots represents a real-world impact location.

When azimuth and elevation regions were cross-tabulated, side-middle (31.6%), rear boss-rim (13.7%), front boss-rim (9.5%), front boss-middle (9.5%), and rear boss-middle (9.5%) were the most commonly impacted regions. Two of these locations fall below the test-line (Table 1).

**Table 1.1** Average azimuth and elevation for the five most common impact locations in the sample of damaged helmets.

| **Impact Location** | **Azimuth (θ)** | **Elevation (ρ)** |
|---|---|---|
| Front Boss-Rim | 44.5º ± 12.8º | 25.4º ± 4.2º. |
| Front Boss - Middle | 48.86 ±10.4 | 38.37 ± 7.11 |
| Side-Middle | 87.1º ± 10.7º | 42.7º ± 7.9º |
| Rear Boss - Middle | 135.86 ±16.52 | 42.04 ± 9.24 |
| Rear Boss-Rim | 137.0º ± 13.5º | 20.3º ± 7.5º |

We tested helmet performance at the three most commonly impacted helmet regions in our real-world sample of damaged helmets. Test locations were chosen to include one of the three most populated azimuth bins. New helmets were tested in the side-middle, rear boss-rim and front boss-rim/front boss-middle (referred to as the front boss location herein). The front boss-rim and front boss-middle were combined for impact testing because the impact frequency was the same in both of these bins. The rear boss-rim was chosen over the rear boss-middle because it had a higher impact frequency and they reside in the same azimuth bin. The average PLA was 214.9 g ± 20.8 g at the side-middle, 191.5 g ± 24.2 g at the rear boss-rim, and 228.0 g ± 39.6 g at the front boss. The highest recorded PLA (318.8 g) was at the front boss. This was the only test that exceeded the 300 g threshold. (Figure 3).

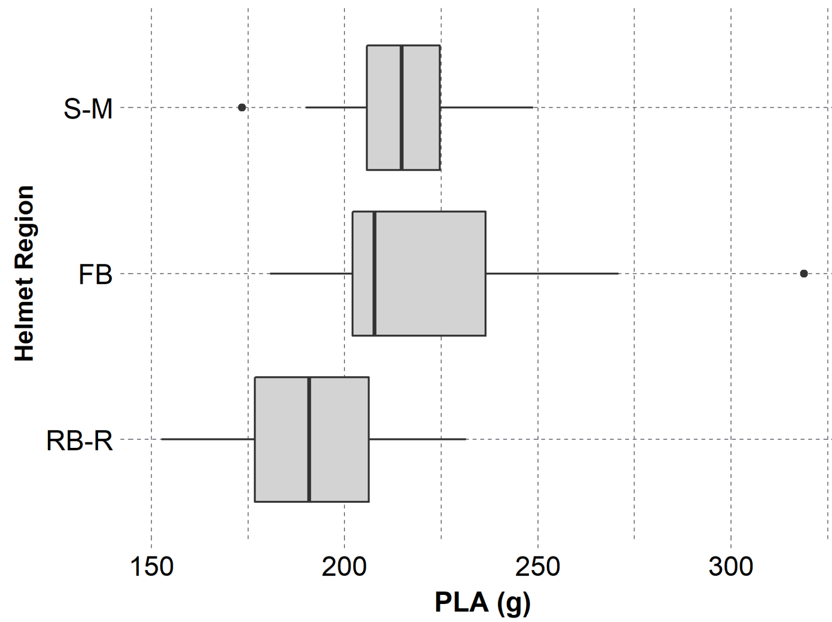


**Figure 1.3**. Helmet performance at each impact region determined by PLA. The coefficient of variance (COV) at the front boss (FB) (17.8%) and rear boss-rim (RB-R) (12.6%) was highest compared to the side-middle (S-M) (9.7%).

To verify the drop location of the helmets used in CPSC testing, impact location was quantified, using the same method described prior, following impact testing. The headform orientation for the side-middle (θ = 64.0°, ρ = 49.9°) and rear boss-rim (θ = 147.0°, ρ = 19.4°) impacts fell within their respective bins. The orientation of the front boss region (θ = 108.1°, ρ = 33.3°) was slightly above the rim region to represent the middle and rim regions. This location is slightly above the test line, a location which is acceptable in CPCSC testing. However, this location included the highest PLA which exceeded 300 g, failing the CPSC testing.

A mixed model ANOVA showed impact location to have a strong effect on helmet performance, measured by PLA ($p = 0.01$). Helmet model, a random effect in our model, also had a strong effect on PLA ($p = 0.01$). The average PLA at the front boss and side-middle locations were not significantly different from one another (ΔPLA= 7.8 g [95% CI: (-14.8 – 30.5)], $p = 0.67$). The rear boss-rim average PLA was significantly lower than the side-middle (ΔPLA= 23.4 g [95% CI: (0.8 – 46.1)], $p = 0.04$) and front boss-rim (ΔPLA= 31.2 g [95% CI: (8.6 – 53.9)], $p =$

0.01). Helmet performance varied heavily between impact regions. The front boss (17.8%) and rear boss-rim (12.6%) locations had higher COVs when compared to the side-middle location (9.7). The rear boss-rim (ΔBrain Injury Risk = 65%, [12% to 77%]) had the highest range of injury risk, but the best performance with the lowest minimum and lowest maximum brain injury risk. The front boss (ΔBrain Injury Risk = 61%, [37% to 98%]) had the highest risk of brain injury (the maximum brain injury risk correlating to the test which exceeded 300 g). The side middle location (ΔBrain Injury Risk = 59%, [26% to 85%]) had the lowest range of brain injury risk.

## DISCUSSION

In this study, real-world bike helmet impact locations were quantified on a NOCSAE headform, applying the most commonly impacted helmet regions to CPSC standard testing. Helmets were evaluated at regions above and below the current test line.

### Real-world Impact Location

According to the method presented for quantifying bike helmet impact location, the most commonly impacted locations were side-middle, rear boss-rim, front boss-middle, front boss-rim, and rear boss-rim. Studies which used qualitative bin assignment or computational modeling to determine real-world impact locations also found the front-rim portion of the helmet to be most commonly impacted.[13-16] However, compared to these studies, which found that 50% of impact occur at the front rim, the density of impacts at the front rim in this study was much lower. As far as the authors are aware, the rear-rim portion of the helmet has not previously been reported as a common impact location.

### Helmet Performance

One helmet exceeded the CPSC threshold of 300 g at the front boss location (318.8 g). Another helmet exceeded 250 g, the EN and AUS/NZ threshold for failure, also at the front boss location (270.9 g). However, CPSC testing is conducted at a higher velocity than the EN and AUS/NZ testing. It is unknown if that helmet would have exceeded the threshold at the EN and AUS/NZ prescribed velocity of 5.42 m/s. The front boss region experienced the highest average PLA, but was not significantly higher than the side-middle region. When the impact which exceeded 300 g was removed from the analysis, the new average was 214.0 g. This is very similar to the average PLA at the side-middle (214.9 g). The rear-boss rim location experienced the lowest average PLA. Low PLA at the rear boss-rim location was not expected, as the rim region has been found to produce higher PLA at front and rear locations.[18] However, lower PLA is favorable, especially in commonly impacted helmet regions. Increased testing below the rim is recommended to analyze this trend further.

Helmet performance varied heavily between impact regions. High variability in performance at real-world impact locations leaves an unresolved risk of brain injury to cyclists. To examine this pattern further, risk of brain injury (AIS > 4) based on HIC15 was calculated for each impact region. The front boss region presented the highest range of brain injury risk across all helmet models, including the highest overall brain injury risk due to one impact exceeding 300 g. These results align with the patterns found in helmet performance at each location. No helmet region demonstrated both superior helmet performance and low variance in helmet performance, which is ideal in order to provide maximal protection to cyclists.

While bike helmet standards do not test below the test line, supplemental performance testing does. Third party bike helmet ratings aim to provide consumers with comparative performance data which includes impact testing at two locations below the helmet rim, as well as four specific locations above the rim.[21] Helmet manufacturers consider helmet performance near the rim based on this testing, however it is not necessary in order to sell a helmet on the market.

Alternate testing protocols also test helmets at oblique angles measuring linear acceleration as well as rotational velocity.[22-27] The CPSC only considers linear acceleration in their testing, a metric correlated with transient intracranial pressure gradients, and highly associated with skull fracture and focal brain injury such as hematoma or contusion.[28] However, testing helmets on oblique anvils also considers rotational velocity which causes shear strain from relative motion at the skull-brain interface and is associated with diffuse brain injuries such as diffuse axonal injuries, concussion, and swelling.[29-31]

A limitation of this study was only testing each helmet model once at each impact location. Without helmet replicates, conclusions cannot be made about the performance of the individual helmets. Additionally, the helmets in this study do not represent helmets at all price points, as the highest priced helmet in the sample was $60 and high-end helmets can cost hundreds of dollars. Although, it has been shown that more expensive bike helmets models do not correlate to improved performance.[32] Lastly, this study aimed to improve upon the current subjective methods used to identify bike helmet impact location. Although this method is highly quantitative, identifying each impact location was partially subjective. The crush depth was inspected without any objective measure to certainly identify the precise point of max crush. Completely objective and computational methods, such as computed tomography, has been used to calculate the exact point of maximum crush in damaged helmets. However, the cost and time expense of CT scanning and scan rendering limits this method to be widely used. The method presented in this paper is much more time efficient and cost effective.

**Conclusion**

Real-world bike helmet impact locations were quantified and a sample of new helmets were tested at the most commonly impacted locations. Two of the five most commonly impacted locations were on the rim, a helmet region not required to be tested for CPSC certification. This study found high variance in helmet performance between commonly impacted helmet locations above and below the test line.

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**APPENDIX A**

**Table A.1** Impact locations (azimuth and elevation), event descriptions, and injury descriptions for each damaged helmet. Relevant information was included as it was stated in the note for each case. Cells without data either did not contain a note, or they did not give information relevant to that column. Positive azimuth values indicate a right-side impact, negative azimuth values indicate a left-side impact.

| Helmet Number | Elevation (degrees) | Azimuth (degrees) | Helmet Region | Event Description | Injury Description |
|---|---|---|---|---|---|
| 1 | 44.0 | 78.8 | Side-Middle | N/a | N/a |
| 2 | 46.6 | -161.2 | Rear-Middle | N/a | N/a |
| 3 | 59.8 | -19.9 | Front-Middle | Low speed crash | N/a |
| 4 | 33.3 | 98.1 | Side-Middle | Fell from bicycle due to hole in street, hit right side of head on stop sign. | Bump and fractured wrist |
| 5 | 41.0 | 87.4 | Side-Middle | Front wheel lost grip and fell to right side. | Road rash on right side of body |
| 6 | 46.7 | 79.7 | Side-Middle | Hit pot hole and lost control. Slid a short way | Lost skin and gash on right elbow, hit right side of helmet |
| 7 | 45.0 | -152.8 | Rear Boss-Middle | N/a | N/a |
| 8 | 31.1 | 114.2 | Rear Boss-Middle | Ran into another biker head on and was sent flying forward into a ditch | Day after crash developed headache, sensitive to bright light, screens, and loud noises |
| 9 | 35.2 | 83.3 | Side-Middle | Lost balance on uneven surface and fell right | Broken collarbone and tore ligaments in shoulder |
| 10 | 62.0 | 65.3 | Front Boss-Top | N/a | N/a |
| 11 | 51.6 | -84.5 | Side-Middle | N/a | N/a |
| 12 | 30.3 | -160.6 | Rear-Middle | Hit pot hole to be bucked forward falling towards the left | Skin loss left hip, leg, and forearm, sore body and neck |
| 13 | 37.6 | -96.1 | Side-Middle | riding on bike path about 10-12 mph | knee took brunt |
| 14 | 55.8 | 18.5 | Front-Middle | Hit by a car at a slow speed | N/a |
| 15 | 24.8 | 177.3 | Rear-Rim | Car stopped in front of bike and bike tried to stop, landed on back | road rash, small cut on back of head |
| 16 | 50.4 | -136.4 | Rear Boss-Middle | Going fast, started turning left and leaned | Slight concussion, sensitivity to noise and |

| | | | | | |
|---|---|---|---|---|---|
| | | | | into turn, hit and slid on left side | light, and headache. Bump to head |
| 17 | 34.4 | -88.4 | Side-Middle | Another biker contacted right leg and hip, fell to left (shoulder then head) | Left shoulder and head hit. No head injuries |
| 18 | 74.1 | -46.0 | Front Boss-Top | riding around a corner and crashed, hit head | Broke shoulder and pelvis |
| 19 | 80.6 | -76.6 | Side-Top | N/a | Mark above left eye, tossed off bike landed on back |
| 20 | 24.1 | -67.0 | Front Bos-Rim | Flipped over handle bars and landed on face | Broke cheekbone |
| 22 | 50.3 | 106.9 | Side-Middle | N/a | N/a |
| 23 | 17.9 | -140.2 | Rear Boss-Rim | "Wrecked" going through a left turn, bike out from underneath to the right, hit back left head | N/a |
| 24 | 38.5 | -73.3 | Side-Middle | Full flip of the bike, fell forward to the side with bike on top rolled onto shoulder and back | Bruising and stretched ligaments in collar bones |
| 25 | 35.3 | 43.5 | Front Boss-Middle | N/a | N/a |
| 26 | 51.9 | -87.4 | Side-Middle | Caused by a driver - front wheel bent to the left | Road rash left arm, bump to head |
| 28 | 32.1 | -82.0 | Side-Middle | Going over 45-degree railroad crossing | Doesn't remember event 30 min before or after |
| 29 | 47.1 | 68.1 | Side-Middle | Turned corner going ~25mph, hit gravel patch and bike came out from under | Road rash |
| 31 | 28.4 | -14.6 | Front-Rim | Accident with car, fell head first into asphalt | N/a |
| 32 | 75.3 | 176.7 | Rear-Top | N/a | N/a |
| 33 | 41.0 | 156.9 | Rear Boss-Middle | N/a | N/a |
| 34 | 37.4 | 179.0 | Rear-Middle | N/a | N/a |
| 35 | 33.0 | -55.7 | Front Boss-Middle | Front tire grazed asphalt and crashed at roughly 15mph, head struck asphalt | Head struck asphalt, no head injury |
| 36 | 26.2 | 53.4 | Front Boss-Rim | Was cut off on a turn, braked hard, contacted back wheel, came off head first, no roll | Bruise to side of eye just below the line where the helmet stops |
| 37 | 26.5 | -44.5 | Front Boss-Rim | Braked suddenly, flipped over handlebars onto the ground | Road rash, sore muscles |
| 38 | 51.5 | -48.2 | Front Boss-Middle | N/a | N/a |
| 39 | 53.0 | -89.7 | Side-Middle | Hit pothole, landed on head | Multiple abrasions |
| 40 | 48.9 | 9.1 | Front-Middle | bunny hopping barriers, back wheel touched and hit face | N/a |
| 41 | 21.3 | -102.4 | Side-Rim | Bike came out from under the rider, ran off road, fell sideways off bike | N/a |
| 42 | 46.3 | 87.0 | Side-Middle | Chain reaction crash in front of rider, went over | N/a |

| | | | | | |
|---|---|---|---|---|---|
| | | | | the bars, ran over rider in front of him | |
| 43 | 27.1 | -132.4 | Rear Boss-Rim | While riding with a group, hit a rough patch, lost control and crashed. hit head twice on pavement | Hit head on pavement |
| 44 | 44.4 | -87.1 | Side-Middle | Thrown under semi-truck cab as it made a right turn into the bike | Hospitalized, bumps, bruises, lacerations on right side from knee to head, contusions at ear and down jaw |
| 45 | 27.3 | -129.5 | Rear Boss-Rim | N/a | N/a |
| 46 | 47.7 | 175.9 | Rear-Middle | N/a | N/a |
| 47 | 17.2 | 68.0 | Side-Rim | N/a | N/a |
| 48 | 29.4 | 124.7 | Rear Boss-Rim | N/a | N/a |
| 49 | 53.9 | 89.8 | Side-Middle | N/a | N/a |
| 50 | 14.5 | -157.8 | Rear-Rim | N/a | N/a |
| 51 | 38.5 | 32.1 | Front Boss-Middle | N/a | N/a |
| 52 | 31.4 | -108.3 | Side-Middle | N/a | Went to hospital, headache |
| 53 | 18.5 | 121.6 | Rear Boss-Rim | Hit a pedestrian at the top of a flyover and rolled backwards, hit head on metal gate | Neck pain |
| 54 | 59.5 | -116.2 | Rear Boss-Middle | Crashed with car head on, bike going 20mph and car going 30mph, flew about 30 feet, head and bike bounced off windshield | Broken ribs 2-7 on left side, scapula, clavicle, parietal bone in skull, minor brain bleeds, memory loss for days after accident |
| 55 | 34.2 | -111.2 | Side-Middle | Dog got under wheel causing him to wipe out | N/a |
| 56 | 26.4 | 149.6 | Rear Boss-Rim | Hit a metal fence that was separately two diverging paths, landed on pavement | No memory of crash, concussion, black eye, stitches above right eye, inside lower lip, and chin |
| 57 | 40.3 | -84.8 | Side-Middle | Ran off the road by a truck, head bounced off the pavement | N/a |
| 58 | 24.5 | 83.1 | Side-Rim | N/a | N/a |
| 59 | 27.7 | 42.3 | Front Boss-Rim | N/a | N/a |
| 61 | 39.4 | -46.0 | Front Boss-Middle | Smashed head on ground | Smashed head near temple/hairline, black eye, possibly concussed |
| 62 | 23.9 | 114.6 | Rear Boss-Rim | Ran over cones on a bike race track | Road rash, broken clavicle |
| 63 | 15.3 | -55.0 | Front Boss-Rim | While riding down a steep decline, went over handlebars, slammed into ground, hitting head | Hit head on ground |
| 64 | 29.4 | -25.8 | Front Boss-Rim | Hit a rut in the road | N/a |
| 65 | 40.9 | -148.9 | Rear Boss-Middle | N/a | N/a |
| 66 | 56.7 | -78.9 | Side-Middle | Primary contact point left side | Thumb injury requiring surgery |
| 67 | 30.3 | 10.2 | Front-Middle | Downhill section of mountain biking, landed on face and right shoulder, dragged against the ground pulling the visor off | Landed on face and right shoulder |

| | | | | | |
|---|---|---|---|---|---|
| 68 | 34.5 | 161.6 | Rear-Middle | Hit gravel, fell to the side | Broken collarbone |
| 69 | 32.5 | -135.2 | Rear Boss-Middle | Riding maybe 15mph, stopped cold and thrown to left onto road | N/a |
| 70 | 26.9 | 34.7 | Front-Rim | N/a | N/a |
| 71 | 24.2 | 46.1 | Front-Rim | skidded to a halt, head was the first thing to hit pavement, | Head was first thing to hit, road rash, concussion |
| 72 | 27.7 | -88.5 | Side-Rim | Crashed into shoulder first then head whipped into ground | Crashed into shoulder first, head whipped into ground |
| 73 | 20.8 | -129.7 | Rear Boss-Rim | Around right hand 90 deg corner at a moderate speed, landed heavily on left side | Landed on left side shoulder and head, 2 bumps on head (one upper temporal left area other occipital left area) |
| 74 | 40.8 | -106.3 | Side-Middle | N/a | N/a |
| 75 | 49.0 | -83.7 | Side-Middle | Drifted right from blinking with sweat in eye, went down onto asphalt | Road rash, three broken posterior ribs, frontal rib fracture with fractured cartilage |
| 76 | 35.8 | -83.8 | Side-Middle | N/a | N/a |
| 77 | 10.0 | -151.5 | Rear Boss-Rim | Right handlebar hit a pole, throwing the rider off the bike, hit the back of head | Fell backward on head and got concussion |
| 78 | 34.6 | 87.4 | Side-Middle | N/a | N/a |
| 79 | 23.1 | -15.2 | Front-Rim | Coming down banked corner, went too fast over jump | N/a |
| 80 | 22.8 | -157.3 | Rear Boss-Rim | N/a | Slid on the sand, crashed on hip and shoulder, bounced twice on head |
| 81 | 35.8 | -86.2 | Side-Middle | N/a | N/a |
| 82 | 36.8 | 68.2 | Side-Middle | ~20 mph, hit a defect in the trail and was catapulted into 12' high wall | Slight bruise on right forehead, A-C joint separation in right shoulder, three broken ribs in front of shoulder, giant hematoma on top of right pelvis |
| 83 | 22.7 | -135.1 | Rear Boss-Rim | N/a | N/a |
| 84 | 30.5 | -59.6 | Front-Middle | Moved to the right to avoid a car and hit a pot hole, bike flipped onto side, head and body hit pavement | N/a |
| 85 | 44.8 | -117.2 | Rear Boss-Middle | N/a | N/a |
| 86 | 34.7 | -179.1 | Rear-Middle | Passed out from dehydration | N/a |
| 87 | 28.0 | 31.9 | Front Boss-Rim | N/a | N/a |
| 88 | 48.2 | 54.8 | Front Boss-Middle | N/a | N/a |
| 89 | 28.2 | 173.0 | Rear-Rim | N/a | N/a |
| 90 | 12.0 | -156.2 | Rear Boss-Rim | Passed out from dehydration | N/a |
| 91 | 33.1 | 36.6 | Front-Middle | N/a | N/a |
| 92 | 22.7 | 171.8 | Rear-Rim | N/a | N/a |
| 93 | 42.4 | -76.8 | Side-Middle | N/a | N/a |
| 94 | 43.9 | -80.6 | Side-Middle | N/a | N/a |
| 95 | 4.7 | 138.1 | Rear Boss-Rim | N/a | N/a |

| | | | | | |
|---|---|---|---|---|---|
| 96 | 35.8 | -63.1 | Front-Middle | N/a | N/a |
| 97 | 27.7 | -85.7 | Side-Rim | N/a | N/a |
| 98 | 59.2 | 89.1 | Side-Middle | N/a | N/a |
| 99 | 33.1 | 144.9 | Rear Boss-Middle | N/a | N/a |

CHAPTER 2

# Laboratory Reconstructions of Real-world Bicycle Helmet Impacts

## ABSTRACT

The best way to prevent severe head injury while cycling is to wear a bike helmet. To reduce the rate of head injury in cycling, knowing the nature of real-world head impacts is crucial. Reverse engineering real-world bike helmet impacts in a laboratory setting is an alternative to measuring head impacts directly. This study aims to quantify helmet damage with CT scanning and replicate real-world damage with a custom, oblique test rig to simulate real-world bike helmet impacts. Damaged helmets were borrowed from a helmet manufacturer who runs a helmet warranty program. Each helmet was CT-scanned and the damage metrics were quantified. Helmets of the same model and size were used for in-lab reconstructions of the damaged helmets where normal velocity, tangential velocity, peak linear acceleration (PLA) and peak rotational velocity (PRV) could be measured. For each damaged helmet, a multiple linear regression (MLR) was created using the damage metrics from the in-lab tests to predict each velocity and kinematic. These equations were used to predict the impact kinematics and velocities for each real-world damaged helmet. Average normal velocity (3.51 m/s), tangential velocity (2.54 m/s), PLA (108.01 g), PRV (15.72 rad/sec) were calculated based on a sample of 23 helmets. Within these head impact cases, five notes reported a concussion. The average PLA and PRV for concussive cases versus other impacts were not significantly different, although the averages for the concussive cases (PLA = 111.4 g, PRV = 18.5 rad/sec) were slightly higher than those without concussion (PLA = 107.1 g, PRV = 15.0 rad/sec). The concussive cases were not indicative of high magnitude impact kinematics.

## INTRODUCTION

Cycling is a popular recreational sport, mode of transportation, and form of exercise. Bike crashes are rare, but they can result in mild to serious injuries or even death when they occur. Head injury is present in the majority of bike crashes which result in death.[1,2] The best way to prevent severe head injury while cycling is to wear a bike helmet.[3-8] Helmets aim to decrease the energy delivered to the head upon impact. Historically, helmets have successfully reduced linear acceleration of the head associated with focal injuries to the brain, such as hematoma or contusion.[9]

Bike helmet regulations were designed to ensure bike helmets manage the energy transferred to the head during impacts. The standard set by the Consumer Product and Safety Commission (CPSC) says that helmets must not exceed a peak linear acceleration of 300 g (<50% risk of skull fracture) during testing.[10] However, rotational accelerations result in shear forces within the brain and are associated with diffuse brain injuries, including concussions, that are not considered in helmet standards.[11] Epidemiological studies have estimated that cycling accounts for 19.45% of all sports-related concussions, the most of any sport.[12]

New helmet technologies have been introduced to the market in recent years, such as the Multi-directional Impact Protection System (MIPS® AB, Täby, Sweden) and WAVECEL™.[13] Both of these systems intend to reduce the rotational head kinematics resulting from impact. Mitigating the kinematic magnitudes is crucial to lowering concussion incidence. Studies evaluating head impact kinematics in other sports have found that concussions occur over a wide kinematic magnitude range, with variance depending on many factors.[14-16] Data describing the concussive kinematics from cycling-related head impacts are lacking.

Collecting impact data for real-world head impacts is challenging. It is impractical to put sensors inside of bike helmets due to the low occurrence rate of crashes. Reverse engineering bike helmet impacts in a laboratory setting is an alternative to measuring head impacts directly. In the past, helmet damage reconstruction studies have been limited by unrealistic test rigs or simplified damaged measurement techniques.[17,18] Bland et al. conducted in-lab reconstructions of bike helmets using CT scanning to quantify helmet damage and an oblique test rig to simulate the impacts. CT scanning is an objective and precise method to measure damage characteristics of bike helmets.[19] Oblique impacts are a better representation of real-world bike helmet impacts than impacting on a flat surface.[20-23] The study conducted by Bland et al. presented a novel technique to investigate head impact boundary conditions. Helmet were collected from hospitals that cyclists were admitted to. This study aimed to expand upon the sparse data describing cyclist head impact kinematics through damage reconstructions of helmets collected through a helmet manufacturer's warranty program.

## METHODS

Bike helmets damaged in real-world crashes were collected through a manufacturer warranty program. The damaged helmet and a note (if one were given by the returning customer) describing crash details were evaluated for each reconstruction. Helmets with no apparent damage, which was determined by searching for scraping on the shell or crush of the EPS liner, were not used in this study.

### Quantifying Helmet Damage

Each helmet was CT scanned (Aquilion, Canon Medical Systems, Tustin, CA: 120 kV, 200 mA, 0.625 9 0.625 mm pixel spacing, 0.5 mm slice thickness) along with a matching undamaged helmet of the same model and size. The scans were segmented in MIMICS 23.0 software (Materialise, Leuven, Belgium) to isolate the EPS foam liner from the plastic helmet shell and surrounding environment. The foam liner corresponded to Hounsfield units (HU) of -950 to -850. Additional automatic and manual editing of the foam liner was done when necessary. Liner masks were converted into a 3D surface mesh model (> 600,000 triangular elements) and imported into 3-Matic 15.0 (x64) (Materialise, Leuven, Belgium). Each damaged helmet model was aligned with the matching undamaged helmet model. The damage metrics were measured by subtracting the damaged helmet measurements from those of the undamaged helmet. The metrics used to quantify helmet damage were crush depth, crush area, crush volume, scrape length, and centeredness of the point of maximum crush. Damage metrics were quantified using the methods described in Bland et al.[24]

**Impact Testing**

Multiple undamaged helmets of the same model and size were purchased for each damaged helmet. Anywhere from three to eight new helmets were used for damage replication per damaged helmet. An oblique impact rig was used for the in-lab damage replications. The impact surface angle was adjustable in increments of 5° between 0° and 60° relative to the horizontal of the impact surface. National Operating Committee on Standards for Athletic Equipment (NOCSAE) headforms in small (53.4 cm circumference), medium (57.6 cm), and large (61.4 cm) were used depending on the damaged helmet size and manufacturer fit recommendations. NOCSAE headforms are biofidelic and are commonly used in sports helmet testing.[25] Multiple impact surfaces were used to produce different types of helmet damage. 80-grit sandpaper was used to simulate pavement and create long scraping profiles. A rough surface created from sand and rocks in epoxy was used to imitate gravel and create focal impacts. Curbstone and hemispheric anvils were also available, but not necessary to recreate damage for this sample of helmets.

The headform was positioned so that the impacts were body-driven, meaning the head was leading the body upon the impact, unless the note indicated otherwise. Positioning of the helmet was measured using a dual-axis inclinometer (DMI600, Omni Instruments, Dundee, UK) for high replication precision between tests. The resultant impact velocity was measured using a photogate (BeeSpi V, NaRiKa Corp., Tokyo, Japan). Impact kinematics were collected at 20 kHz using three linear accelerometers (Endevco 7264B-2000, Meggitt Sensing Systems, Irvine, CA) and a tri-axis angular rate sensor (ARS3 PRO-18K, DTS, Seal Beach, CA) at the headform center of gravity (CG). The kinematic data from each helmet test were recorded using a TDAS SLICE PRO SIM data acquisition system (DTS, Seal Beach, CA).

For each test, the scrape direction and helmet location were matched to the original damage. However, the magnitude of the damage metrics (crush depth, crush area, crush volume, scrape length, and centeredness) were replicated at a lower and higher magnitude than the damage metrics from the original helmet. A combination of anvil angle and drop height were used to adjust these magnitudes.[26] The damage metrics of the in-lab tested helmets were quantified using the same process as the original damaged helmets which is described above. If the point of maximum crush was located more than half the distance of the crush area radius away from the original point of maximum crush, the trial was omitted.

**Data Processing**

Linear acceleration was processed using a channel frequency class (CFC) 1000 filter (SAE J211) and rotational velocities were processed using a CFC of 175. The drop data was processed using a custom MATLAB (R2020a, Mathworks Inc, Natick, MA) script to obtain the peak linear acceleration (PLA), peak rotational velocity (PRV), and duration of impact. The normal and tangential velocities were calculated based on the angle of the anvil and the resultant impact velocity.

**Data Analysis**

For each damaged helmet, correlation analyses were computed between each damage metric and each velocity and kinematic. The damage metric(s) with the highest correlation coefficient and their interactions were used as parameters in a multiple linear regression (MLR) model for each velocity and kinematic. The model with the highest R-squared value was used to predict the impact velocity or kinematic for the original damaged helmet by plugging in the original damage metric(s).

For example, to estimate normal velocity of one helmet's impact, we determined which damage metric(s) had the highest correlation to normal velocity during our in-lab tests. Then that damage metric, or a combination of multiple damage metrics, was used to create a linear model with the damage metric as the independent variable and the normal velocity as the dependent variable. The damage metric(s) from the original helmet was then used in the model to compute normal velocity. The maximum number of parameters for each model was two less than the number of in-lab tests for that helmet. This process was conducted to estimate the normal velocity, tangential velocity, PLA, and PRV for each damaged helmet. All statistical analyses were conducted in RStudio (V 1.0.136, RStudio, Inc., Boston, MA).

## RESULTS

Impact velocities and kinematics were estimated for 23 helmets damaged in real-world bike crashes. Of these helmets, 21 helmets included a note with some description of the incident, one helmet included a picture of the crash scene and damage to the bike without a note, and one helmet did not include any information. 16 cases reported some sort of injury, including 5 concussions.

**Damage Characteristics**

Five damage metrics were used to characterize helmet damage (Figure 1). Crush depth had a median of 5.0 mm [IQR = 2.5 – 7.1 mm], crush area had a median of 25.73 $cm^2$ [IQR = 13.2 – 36.3 $cm^2$], crush volume had a median of 8.5 $cm^3$ [IQR = 3.5 – 13.9 $cm^3$], scrape length had a median of 5.3 cm [IQR = 4.2 – 6.9 cm], and centeredness had a median of 1.2 [IQR = .6 – 2.3]. The case which resulted in the maximum crush depth was crushed in the rear region of the helmet. The maximum values for crush area and crush volume were also observed from this case.

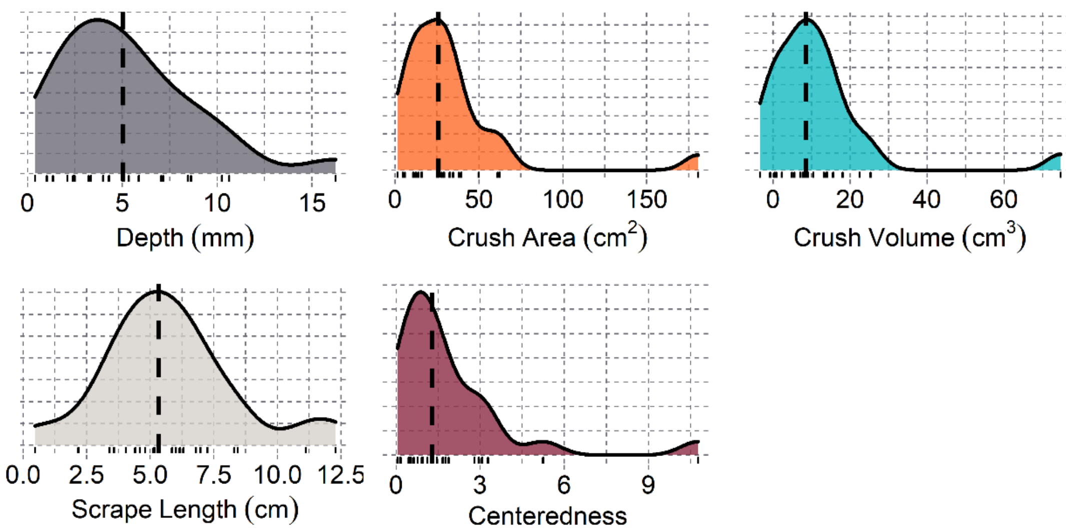


**Figure 2.1.** The distributions of damage metrics measured from a sample of helmets damaged in real-world bike accidents. The dashed line indicates the median value for each damage metric.

The two impact surfaces were almost evenly split between cases: 80-grit sandpaper (12 cases) and the rocky surface (11 cases). The majority of helmets fit a medium headform (13), followed by small (6) and large (4). An average of four undamaged helmets were used to replicate each case. The smallest number of replications for a case was three helmets to calculate the MLR. Within the replications for one case, the resulting damage metrics needed to range above and below the damage metrics from the original helmet. Some cases required additional tests to reach this goal. The most replications for one helmet case was eight, but two of those replications were eventually deemed unusable based on the large difference between points of maximum crush. The average impact angle was 37° with a minimum angle of 15° and a maximum of 60°.

Overall, crush area and crush depth were the damage metrics most commonly used to predict impact velocities and kinematics (including interaction terms). Normal velocity was most commonly estimated by crush depth and crush area, closely followed by crush volume. Tangential velocity was most commonly estimated by crush depth, closely followed by crush area and scrape length. PLA was most commonly estimated by crush area. PRV was most commonly estimated using centeredness, closely followed by scrape length and crush depth.

High correlations between one damage metric and one impact characteristic were not observed for every case. Some cases used a combination of loosely correlated damage metrics to create an MLR with a moderate (0.4 - 0.7) R-squared value. The standard errors were normalized (NSE) with the average for each metric to account for the difference in magnitude between each velocity and kinematic. PRV had the highest NSE (12%) of all the impact characteristics (Normal Velocity = 6%, Tangential Velocity = 8%, PLA = 7%.

**Impact Characteristics**

We were able to estimate normal and tangential velocity, PLA, and PRV for all 23 helmets (Figure 2). The averages for each velocity and kinematic were calculated: normal velocity (3.5 m/s), tangential velocity (2.5 m/s), PLA (108.0 g), PRV (15.7 rad/sec).

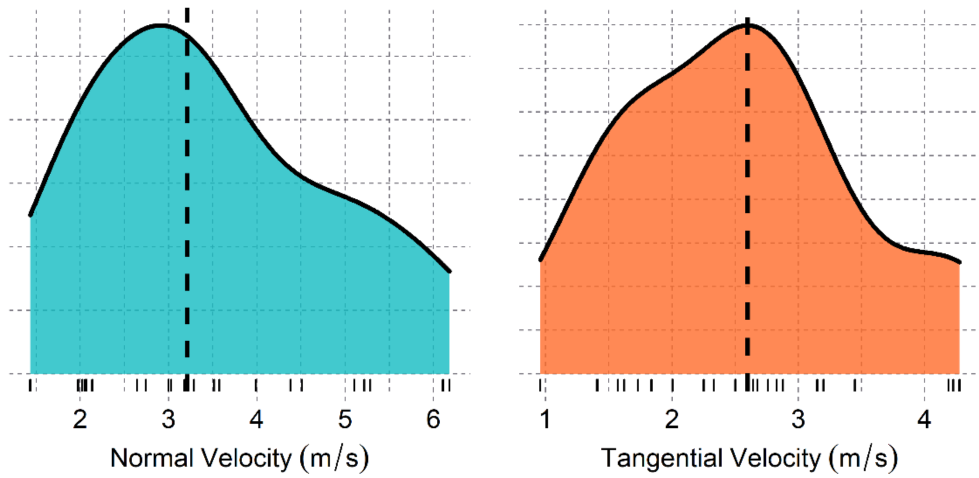


**Figure 1.2.** The distribution of normal velocity and tangential velocity for 23 real-world bike helmet impacts. The dashed lines represent the median value of each metric.

Within these head impact cases, five notes reported a concussion. Two of these cases reported being taken to the hospital and diagnosed with a concussion. One case reported a headache and sensitivity to light and noise, which lasted for two days, which we interpreted as a concussion. One case had extensive loss of memory extending from before the crash to after the hospital visit, which we also interpreted as a concussion. One case reported a concussion without further details.

The impact kinematics from the concussive cases were compared to the rest of the sample. The kinematics for the concussive cases were all within the range of the kinematics for the impact cases (Figure 3). The average PLA and PRV for concussive cases compared to the rest of the sample were not significantly different, although the averages for the concussive cases (PLA = 111.4 ± 34.5 g, PRV = 18.5 ± 7.0 rad/sec) were slightly higher than those without concussion (PLA = 107.1 ± 44.0 g, PRV = 15.0 +10.0 rad/sec).

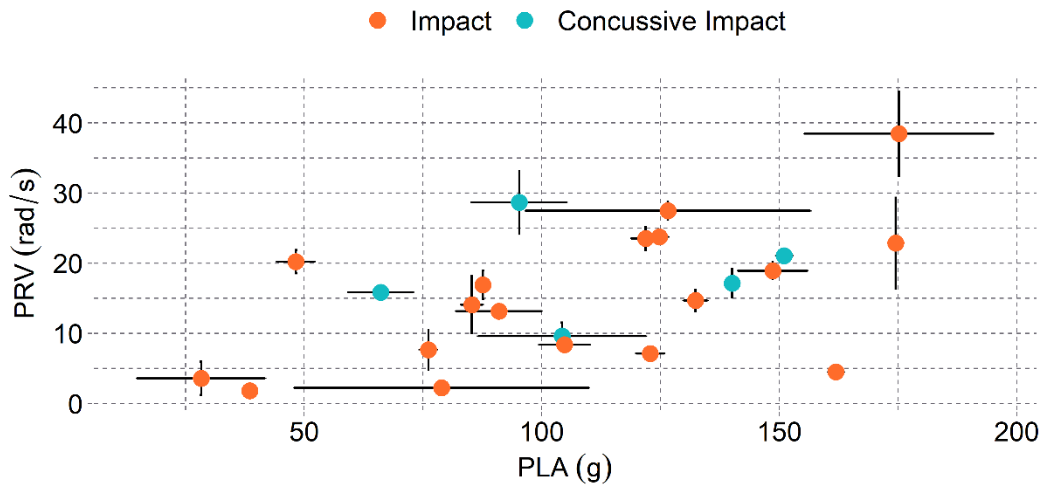


**Figure 2.3.** The relationship between peak linear acceleration and peak rotational velocity for helmeted bike helmet impacts, including concussive cases. The lines emitting from each point represent the standard error of each prediction.

**DISCUSSION**

This study's objective was to estimate the velocities and kinematics of real-world bike helmet impacts using the relationship between damage metrics and impact boundary conditions. The impact velocities estimated in this study align with those estimated using computational simulations[23] and other in-lab helmet reconstructions.[17,24] During standards testing, helmets are dropped at normal velocities of 3.4 m/s and 6.2 m/s. The average normal velocity from this sample was 3.5 m/s, and the maximum value was 6.2 m/s. The velocities used in standard testing are within the range of the velocities in real-world impacts.

Third-party helmet testing systems use oblique impact rigs to test bike helmets. This testing is not necessary to sell helmets on the market, but it gives consumers additional insight into helmet performance past standards testing. These test systems drop helmets onto a 45° anvil to evaluate helmets' ability to mitigate rotational motion of the head. The impact velocity of these tests ranges from 6.3 m/s to 8 m/s.[27-29] These velocities are associated with normal and tangential components ranging from 4.5 m/s to 5.7 m/s on a 45-degree anvil. These velocities are much higher than the average normal (3.5 m/s) and tangential (2.5 m/s) velocities found in this study. However, helmet tests are designed to evaluate helmets at high velocities to quantify performance during high-risk impacts.

When we compared the data between this study and the data in a previous study by Bland et al., we saw the maximum velocities and kinematics tended to be lower in this study in all cases except for normal velocity. The linear metrics (normal velocity and linear acceleration) showed very similar medians between the two samples. However, the rotational metrics (tangential velocity and rotational velocity) were much lower in the current sample. The helmets in this study were borrowed from a helmet manufacturer warranty program, whereas, the helmets in Bland et al. were collected from crashes which resulted in hospitalizations. The sample in Bland et al, most likely included helmets from riders who were traveling at higher velocities directly prior to the crash. This would contribute to the higher rotational forces upon impact. Collecting helmets from a manufacturer warranty program could have resulted in a lower threshold of damage for the helmet to be returned, opposed to collecting helmets from cases which resulted in hospitalizations. This sample variance can be seen in the median tangential velocity and rotational velocities (Figure 4).

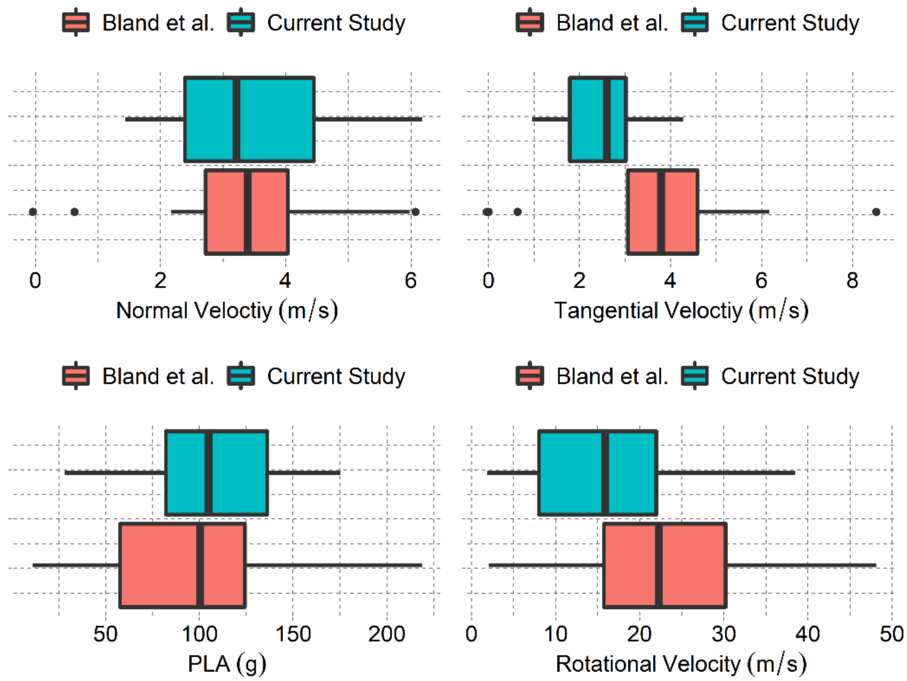


**Figure 2.2.** The estimated impact velocities and kinematics of real-world bike accidents in this study compared to the previous study by Bland et al. The tangential velocity and peak rotational velocity were much lower in the current study. The median of each linear metric (normal velocity and PLA) aligned very well between both studies.

In both Bland et al. and the current study, the average PLA and PRV for the concussive cases were higher than cases without concussion. The PLA for concussive cases (111.3 ± 34.5 g) in this sample was similar to those estimated from Bland et al (109.8 ± 55.0 g). The PRV for concussive cases was higher in Bland et al. (19.3 ± 7.4 rad/s) than the concussive cases in this study (18.5 ± 8.9 rad/s). The average PLA for concussive impacts in this sample (111.4 ± 34.5 g) align with the average PLA for concussive hits in football (104 ± 30 g).[30] Similarly, the average PRV for concussive impacts in this sample (18.5 ± 7.0 rad/sec) aligns with the average PRV found in concussion in American football (22.3 rad/s).[31]

The limitations of this study affect our ability to estimate impact boundary conditions with minimal error. The CT scans used in this study have a resolution of .5mm. This is compounded with the global resolution error in 3-Matic (ranging from .9 mm to .4 mm) when aligning the damaged and undamaged helmets. These measurement errors can affect final estimates from the

MLRs. Additionally, the sample size in helmets was affected by the availability of new helmets of the same model and size as the damaged helmets in our study. We were not able to use multiple donated damaged helmets due to a lack of new matches. This unavailability was due partly to the age of some helmet models that are no longer being produced and party due to the increase in demand for bike helmets during the COVID-19 pandemic. Additionally, one helmet model had metal artifacts within the EPS foam which were too extensive to remove in post-processing, so we could not use the helmet in the study.

The test rig used in this study can account for multiple variables in helmet impacts, including impact surface, angle, and location. However, it is also common for more than one impact to the helmet during a crash. Our test setup was only able to recreate the most severely damaged region, which was assumed to be the initial impact. Additionally, some helmets were so extensively damaged that we could not recreate the crush area or crush volume. At some point, increasing the drop height does not necessarily increase the resulting crush depth, area, and volume. On the other hand, some damage profiles were extremely small. There is a minimum height on the drop tower to ensure the helmet is released from the carriage before impacting the anvil.

The data in this study can inform test methods for improved helmet testing and design. As more test methods are designed to evaluate rotational velocities, real-world impact characteristics are of increasing importance. As helmet design is influenced by both standards testing and supplemental third-party testing, creating test methods that accurately reflect real-world impacts is important to helmet manufacturers. Increasing the amount of available bike helmet reconstruction data, including cases that resulted in head injury, is key to improving helmet testing and design and decreasing the risk of brain injury while cycling.

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## APPENDIX B

**Table B.1** The damage metrics and resulting impact velocities and kinematics for each damage replication.

| Helmet Number | Concussion? | Crush Depth (mm) | Crush Area ($cm^2$) | Crush Volume ($cm^3$) | Centeredness | Scrape Length (cm) | Normal Velocity (m/s) | Tangential Velocity (m/s) | PLA (g) | PRV (rad/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | No | 8.6 | 34.5 | 15.6 | 1.8 | 6.3 | 4.4 | 2.8 | 161.9 | 4.5 |
| 5 | No | 3.3 | 1.5 | 0.8 | 1.5 | 3.4 | 1.4 | 2.0 | 38.5 | 1.8 |
| 15 | No | 16.3 | 180.7 | 74.7 | 1.1 | 6.2 | 6.2 | 2.9 | 175.2 | 38.4 |
| 16 | Yes | 2.1 | 62.4 | 7.7 | 0.4 | 6.0 | 6.1 | 2.7 | 151.0 | 21.1 |
| 17 | No | 2.5 | 25.4 | 0.4 | 0.8 | 4.4 | 2.7 | 2.8 | 122.9 | 7.1 |
| 18 | No | 5.1 | 49.9 | 18.0 | 0.6 | 4.6 | 3.2 | 2.3 | 87.6 | 16.9 |
| 22 | No | 8.5 | 39.4 | 22.4 | 3.1 | 8.4 | 3.5 | 4.2 | 121.9 | 23.5 |
| 23 | No | 1.4 | 5.9 | -0.8 | 10.8 | 3.6 | 2.1 | 1.6 | 48.3 | 20.2 |
| 26 | No | 7.1 | 27.8 | 13.8 | 0.5 | 7.0 | 5.3 | 1.6 | 174.6 | 22.8 |
| 28 | Yes | 0.4 | 13.9 | -0.8 | 3.3 | 5.3 | 2.6 | 2.6 | 104.3 | 9.6 |
| 39 | No | 5.1 | 15.6 | 5.5 | 5.2 | 5.9 | 2.1 | 1.0 | 28.3 | 3.6 |
| 52 | No | 3.2 | 32.7 | 8.5 | 0.2 | 8.3 | 3.6 | 2.5 | 76.1 | 7.7 |
| 54 | Yes | 5.3 | 38.1 | 25.3 | 0.1 | 12.3 | 4.5 | 2.6 | 140.1 | 17.2 |
| 56 | Yes | 10.6 | 10.8 | 2.2 | 1.3 | 0.5 | 3.0 | 1.4 | 95.3 | 28.7 |
| 62 | No | 2.4 | 12.5 | 4.8 | 1.0 | 5.2 | 2.0 | 3.4 | 85.3 | 14.1 |
| 72 | No | 1.0 | 29.3 | -3.4 | 1.7 | 4.0 | 2.1 | 3.1 | 132.4 | 14.7 |
| 73 | No | 10.3 | 28.8 | 13.2 | 1.3 | 3.6 | 5.2 | 3.2 | 126.6 | 27.5 |
| 74 | No | 4.0 | 25.7 | 9.0 | 1.9 | 5.1 | 3.3 | 4.2 | 148.6 | 18.9 |
| 77 | Yes | 2.4 | 12.1 | 7.0 | 0.1 | 2.2 | 2.0 | 1.4 | 66.1 | 15.9 |
| 80 | No | 5.0 | 61.3 | 13.2 | 2.8 | 11.1 | 3.2 | 1.8 | 91.0 | 13.2 |
| 81 | No | 5.9 | 16.2 | 10.4 | 2.9 | 6.8 | 5.1 | 4.3 | 78.9 | 2.2 |
| 82 | No | 7.2 | 24.9 | 14.1 | 0.5 | 7.2 | 4.0 | 2.3 | 124.8 | 23.7 |
| 84 | No | 4.3 | 4.6 | 7.9 | 0.9 | 4.8 | 3.0 | 1.7 | 104.8 | 8.4 |

# CHAPTER 3

# CLOSING REMARKS

## SUMMARY OF RESEARCH

The current research presents a valuable data set for the advancement of bicycle helmet research, design, and testing protocols. Currently, bike helmets are only required to be tested on a flat anvil with a threshold of linear acceleration of 300 g to be certified for purchase in the United States. However, many studies have shown a that oblique impacts which result in tangential velocities and rotational accelerations are more realistic during bike helmet impacts. Oblique impacts also increase risk of concussion based on the resulting shear strain at the skull-brain interface. Improving helmet testing and design to reduce this risk is necessary as cycling becomes increasingly popular.

The first chapter in this thesis quantified impact location of real-world bike helmet impacts. Standards testing has established a test line, below which bike helmets are not required to be tested. This leaves regions of the helmet untested and a risk of unknown performance variability below the test line. By quantifying the impact location of real-world damaged bike helmets, we found that two of the five most commonly impacted locations were below the test line. When we tested helmet performance at the three most commonly impacted locations we saw that impacts at the rim did not indicate poor performance, but it did reveal high inter-location variability. We also observed an impact which exceeded 300 g at the front boss region. This study provides a basis for improving standard helmet testing, as well as, informing helmet manufacturers of the variability in helmet performance based on impact location.

The second chapter of this thesis estimated the impact velocities and resulting linear and rotational kinematics from a sample of real-world damaged helmets. We found that the normal velocities estimated in our study aligned well with the impact velocities used in standard and third-party helmet testing. Of the cases in our sample which resulted in concussion, the PLA and PRV were only slightly, higher than the residual impacts. The results from this sample were compared to those from a similar study by Bland et al. (2020). The median normal velocity and linear acceleration were very similar between the samples, but the median tangential velocity and rotational velocities were much higher in the sample from Bland et al. Increasing the availability of cycling related head impact data is necessary to further advance helmet research and decrease the risk of brain injury while cycling.

**PUBLICATION PLAN**

Each of the preceding chapters will be published in a scientific, peer-reviewed journal or a related conference (Table 3.1)

Table 3.1 Publication plan for research.

| *Chapter* | *Title* | *Journal (Conference)* |
|---|---|---|
| *1* | The range of bicycle helmet performance at real-world impact locations | Journal of Sports Engineering and Technology (Biomedical Engineering Society) |
| *2* | Laboratory reconstructions of real-world bicycle helmet impacts | Annals of Biomedical Engineering |