

Whitewater Helmet STAR: Evaluation of the Biomechanical Performance and Risk of Head Injury for Whitewater Helmets

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Abstract---There are more than 6 million people who participate in whitewater kayaking and rafting in the United States each year. Of these 6 million participants, there are over 50 whitewater related deaths annually, which makes it have one of the highest fatality risks of all sports. The objective of this study was to create a new rating system for whitewater helmets by evaluating the biomechanical performance and risk of head injury of whitewater helmets using the fundamental properties of the STAR system. A total of 21 helmets were selected for this study, and a custom pendulum impactor was used to test the helmets under conditions which are known to be associated with the highest risk of head injury and death. The helmets were tested at 3.1 m/s and 4.9 m/s with impacts to the front, rear, and side for each speed. Each helmet's STAR value was calculated using the combination of exposure and injury risk that was determined by the linear and rotational head accelerations. The calculated STAR values varied between helmets, indicating that some helmets provide better protection than others. Overall, the results show a clear need for improvement in whitewater helmets, and the methodologies developed in this research project should provide manufacturers a path to improving their products.

attained in these activities are acute, and they account for approximately 58% of all whitewater injuries (Spittler, et al., 2020). Acute head injuries occur in these sports from either contact with objects from outside the boat such as rocks, or from contact with other paddler's equipment (Spittler, et al., 2020; EN 1385: 2012). Head, neck, and face injuries are frequent among paddlers and are considered to be the most severe. Of all possible injuries, head injuries are the most life threatening. These dangerous head injuries can cause a participant to become unconscious, which often leads to death due to drowning. The head injuries are so severe that 77% of participants who sustain head injuries require medical attention (Schoen & Stanto, 2002).



Figure 1: Whitewater rafting is one of the most dangerous sports in the United States with over 50 fatalities each year.

Introduction

Whitewater Kayaking and Rafting

There are over 6 million people who participate in whitewater kayaking and rafting in the United States every year (Figure 1) (Spittler, et al., 2020). Of these 6 million participants, there are more than 50 whitewater related deaths each year, which gives the sport one of the highest fatality risks of all sports (Spittler, et al., 2020; Sayour, et al., 2019). As the popularity in whitewater activities grows, the number of injuries, including concussions, also increases. The majority of injuries

The most common mechanism of whitewater head injuries is contact against underwater objects with the frontal/forehead area and the side of the eye socket (EN 1385: 2012). This occurs when a participant either capsizes or falls out of their vessel. Once out of their vessel, the fast moving rapids paired with hidden rigid rocks beneath the water's surface pose a high risk of head injury and death. The highest recorded flow rate in a whitewater river is 5 m/s, which implies that it is very unlikely that any underwater head impact will have a head impact speed greater than 5 m/s (EN

1385: 2012). Because of the high head injury risk, there is an extremely high helmet usage rate among whitewater sports (Spittler, et al., 2020).

EN 1385: 2012 Whitewater Helmet Standard

One of the world's largest certification bodies, the British Standards Institution, created the only standard of testing for whitewater helmets known as EN 1385: 2012. The standard evaluates the helmet's impact protection, durability, and retention. To evaluate the impact protection, helmets are dropped from a height that simulates at least 15 Joules onto the center of a fixed anvil. The standard requires a tridirectional accelerometer to be fitted in the headform, a head impact acceleration recording apparatus, a system to guide the falling helmet, and a non-fixed system that supports a helmeted metal headform that is small through large in size. If a medium sized headform, named 575-J, is being used, the drop height is 0.326 m and the impact speed is 2.53 m/s. The impact speed ranges from 3.11 m/s to 2.22 m/s for the smallest to the largest of the five headform sizes. The mass of the medium headform is 4.69 kg while the masses range from 3.10 kg to 6.09 kg for the smallest to the largest headforms. The circumference of the medium headform is 0.575 m while the circumferences range from 0.495 m to 0.625 m for the smallest to the largest headforms. Upon impact with the anvil, the headforms cannot exceed a measured acceleration of 250 g after data processing and filtering for any of the impact tests and configurations. In order to evaluate durability, additional tests are performed that involve heating and cooling helmets, a water immersion configuration, and radiation exposure. The standard also performed retention tests which evaluate the helmet's ability to stay on participants. Overall, the standard provides many useful and important evaluation processes; however, advances in impact testing could provide more information and an improved characterization of the helmet impact response.

Linear and Rotational Head Acceleration Components

The whitewater helmet standard is like most historical helmet standards in that the impact test

only evaluates linear acceleration (EN 1385: 2012). However, both linear and rotational acceleration occur during head impacts, and many researchers have demonstrated the importance of rotational acceleration relative to brain injury. An example of such researchers is Dr. Post and his colleagues at the Neurotrauma Impact Science Laboratory at the University of Ottawa. By using computational models of the brain, Dr. Post and his research team have shown that rotational acceleration increases the amount of brain deformation (Post, et al., 2013). Recently, helmet testing devices and standards have been created to evaluate both linear and rotational accelerations by the National Operating Committee on Standards for Athletic Equipment (NOCSAE), the National Football League (NFL), and the Virginia Tech STAR helmet rating systems (Bailey, et al., 2020; Pellman, et al., 2006; Bland, et al., 2019; Campolettano, et al., 2020). New algorithms have been created to calculate injury risk from these new tests. For example, the combined probability of injury equations determines risk of concussion by analyzing the peak linear and rotational accelerations (Rowson & Duma, 2013). By lowering both linear and rotational acceleration in laboratory tests, it has been shown that brain injury risk is lowered in real-world head impact events (Rowson, et al., 2014; Bailey, et al., 2020). Given the serious head injuries observed in whitewater sports, both linear and rotational acceleration measures should be analyzed when evaluating the biomechanical performance of whitewater helmets (Schoen & Stanto, 2002).

STAR Helmet Evaluation System

A new helmet evaluation system has been developed by leading researchers at the Virginia Tech helmet lab, who have been testing helmets in a multitude of sports for the past ten years (Rowson & Duma, 2011; Rowson, et al., 2015; Bland, et al., 2019). This method they created combines extensive impact testing that includes the use of an injury risk function as well as exposure data to generate a complete summary of the helmet performance (Rowson & Duma, 2011). This system is called the Summation of Tests for the Analysis of Risk (STAR). For most sports, the system uses the medium NOCSAE headform mounted on a Hybrid III neck. Instrumentation inside the headform

measures linear acceleration and rotational velocity, and the latter is used to determine rotational acceleration. Impact tests are performed at a range of impact locations and energy levels that include both centric and non-centric impact directions. For each impact test, the peak linear and rotational acceleration values are inserted into a brain injury risk function, and that risk is multiplied by exposure to get an overall incidence number (Rowson & Duma, 2013). The STAR equation aggregates all of this data into one number that is used to set the helmet ratings STAR value, with five stars indicating the best available protection. Helmets with higher star ratings do a better job of managing the impact energy and ultimately lowering the linear and rotational acceleration values the head would experience for a given impact. The STAR rating system has been utilized for many sports, such as hockey, soccer, cycling, football, youth football, and flag football (Rowson & Duma, 2011; Rowson, et al., 2015; Bland, et al., 2019; Campolettano, et al., 2020). The appeal of the STAR system is that it clearly differentiates complex helmet performance into usable information for consumers. Moreover, on-field studies have shown brain injury reduction rates in athletes who wear higher rated helmets (Rowson, et al., 2014; Bailey, et al., 2020).

Objectives

There are serious head injuries in whitewater sports and the current standard of testing is very limited. An advanced whitewater helmet rating system is needed to help improve product design and reduce injury risk. The current standard of testing for whitewater helmets provides important evaluation of the helmet's retention and durability, but the impact tests are limited. The maximum head acceleration limit of 250 g in the drop test is very high for a relatively low 15 J impact event. Also, rotational acceleration should be taken into consideration for this standard, because both linear and rotational acceleration are proven to contribute to head injuries like concussions (Post, et al., 2013). As of now, the consumer has no information to differentiate between helmets that have passed the standard, so a publicly available rating system for these helmets is necessary. This new rating system will facilitate the purchase and use of more protective helmets which could decrease the amount

of head injuries in whitewater activities. The objective of this study is to create a new rating system for whitewater helmets by evaluating the biomechanical performance and risk of head injury of whitewater helmets using the STAR system.

Methods and Materials

Whitewater Kayaking and Rafting Helmets

A total of 21 helmet models were purchased from five different manufacturers (Table 1). Two samples of each helmet were purchased for testing for a total test matrix of 42 helmets. The watersport helmets that were chosen for this study were required to be clearly marketed for whitewater use. This was determined through each manufacturer's website and helmet descriptions. The size of each helmet purchased was chosen to match the circumference of the medium NOCSAE head form of 57.6 cm. If two of the sizes for a given helmet overlapped across this value, the larger helmet was chosen. The price and mass of each helmet were recorded before experimentation.

Every helmet used in this study was certified to the EN: 1385: Whitewater Helmet Standard. This ensures that regardless of the outcomes of this research, the helmets still passed the range of basic safety tests included in the standard. This is consistent with previous studies conducted in other sports that benchmarked all helmets tested to other available standards. For example, all football helmets rated have passed the NOCSAE standard (Rowson & Duma, 2011), all hockey helmets rated have passed the Hockey Equipment Certification Council (HECC) standard (Rowson, et al., 2015), and all bicycle helmets rated have passed the Consumer Product Safety Commission (CPSC) standard (Bland, et al., 2019).

Pendulum Impactor Device

A custom pendulum impactor was used to test the helmets under conditions simulating the highest risk of head injury in whitewater kayaking and rafting (Figure 2). The pendulum consists of an arm, pivot point, and an impactor surface. The pendulum provides an extremely repeatable system with an arm composed of 10.16 x 5.8 cm

Manufacturer	Helmet Model	Price (\$)	Mass (g)	Legend
Shred Ready	Fullface Whitewater Helmet	149.95	705	FF
Shred Ready	Outfitter Pro Helmet	49.00	360	O
Shred Ready	Shaggy Helmet	179.95	535	SH
Shred Ready	SESH Helmet	54.95	495	SE
Shred Ready	Halfcut Whitewater Helmet	99.95	505	H
Shred Ready	Fullcut Whitewater Helmet	110.00	585	FC
Shred Ready	Super Scrappy Whitewater Helmet	89.95	485	SS
WRSI	Trident Composite	199.95	565	T
WRSI	Moment Fullface	179.95	805	M
WRSI	Current Pro	139.95	715	CP
WRSI	Current	119.95	595	C
NRS	Chaos Side Cut Helmet	79.95	565	CS
NRS	Chaos Full Cut Helmet	69.95	510	CF
NRS	Havoc Livery Helmet	49.95	420	HL
Sweet Protection	Rocker Fullface Helmet	329.95	730	RF
Sweet Protection	Rocker Helmet	229.95	530	R
Sweet Protection	Strutter Helmet	199.95	515	ST
Sweet Protection	Wanderer Helmet	149.95	580	W
Sweet Protection	Sweet Rocker - Dagger Edition	259.99	530	SR
Gath	Gath Gedi	189.00	430	G
Gath	Gath RV	209.00	550	RV

Table 1: All 21 helmet models purchased for testing with their respective price and weight

rectangular aluminum tubing and a 16.3 kg impacting mass at its end. The length of the arm from the center of its pivot point to the center of its impacting mass is 190.5 cm. The pendulum arm has a total mass of 36.3 kg and a moment of inertia of 72 kg m². The impactor face is constructed of nylon and has a diameter of 20.3 cm and a radius of curvature of 12.7 cm. This contact surface is designed to mimic a rigid surface a whitewater participant might impact, while also maximizing repeatability and reproducibility of the tests.

The headform was connected to the data acquisition system to the left of the device. The pendulum impactor arm was elevated by using a winch system fixed to an electromagnet that could hold or release the pendulum arm. The height of the pendulum head corresponded to either the 3.1 m/s impact speed or the 4.9 m/s impact speed. This speed was determined by the angle of the pendulum arm. An angle of 30 degrees correlated to a 3.1 m/s

impact speed and an angle of 60 degrees correlated to a 4.9 m/s impact speed. The impact speed was validated using a speedometer positioned directly before the impact site.

Head and Neck Configurations

Each whitewater helmet was positioned on a medium NOCSAE headform according to each helmet's respective manufacturer fitting guidelines. The NOCSAE headform was utilized because its shape allows for a very realistic fit between the helmet and headform. The headform was mounted to a Hybrid III 50th percentile neck using a custom adapter plate that provided the anatomically accurate relative locations of the occipital condyle pin and headform center of gravity (CG). The mass of the adaptor plate was made to be equal to the material removed for this modification. The head

and neck assembly was mounted on a sliding mass that was designed to simulate the effective mass of the torso during a head impact, thus providing the best biofidelic impact configuration. This sliding mass was mounted to an adjustable table commonly used for impact testing (Biokinetics, Ottawa, Ontario, Canada). In contrast to most standard certification tests, this pendulum system allows and accounts for linear and rotational motion.

To measure the head impact kinematics, the headform was instrumented with a six degree of freedom sensor package consisting of three accelerometers and three angular rate sensors (6DX-Pro, DTS, Seal Beach, CA). Data was sampled at 20,000 Hz and filtered using a 4-pole Butterworth low pass filter according to SAE J211, with a cutoff frequency of 1650 Hz (CFC 1000) for accelerometer data and 256 Hz (CFC 155) for angular rate sensor data. The angular acceleration values were determined by differentiating the angular rate data. Resultant values were calculated for linear (g) and rotational (rad/sec²) acceleration.

Impact Configurations

Six impact configurations were used to test the helmets. These configurations were defined by three different impact locations at two different speeds. The front, side, and rear helmet sites were impacted to cover the range of the possible impact locations for a whitewater helmet (Figure 3). Two impact speeds of 3.1 m/s and 4.9 m/s were selected to replicate a medium and high impact. The velocity of 4.9 m/s was chosen as the high impact speed because the highest recorded flow rate of a river is 5 m/s (EN 1385: 2012). Each helmet was only impacted once at each site to ensure that any deformation caused by testing did not affect any future tests. This resulted in six tests per helmet model for a total test matrix of 127 tests. The laboratory's mandatory safety guidelines were followed for each test. These guidelines included safety lockout procedures to ensure the safety of all participants involved.

Whitewater STAR Equation

Similar to previous STAR systems in other sports, each helmet's STAR value was calculated using the resultant linear and rotational acceleration

for each respective test (Equation 1). For this equation, E represents exposure; L represents the impact locations; V represents the impact velocity; and R represents the risk of concussion defined by the linear (a) and angular (α) head acceleration for each configuration.

$$Whitewater\ STAR = \sum_{L=1}^3 \sum_{V=1}^2 E(L, V) * R(a, \alpha)$$

The risk of concussion for a given test was calculated through the risk function using the resultant linear and rotational head accelerations observed (Equation 2). The risk function used in this equation includes both linear and rotational head acceleration because they are both correlated and predictive of concussion (Rowson & Duma, 2013). This function was developed from high school and collegiate football head acceleration data. A multivariate logistic regression analysis modeled risk as a function of linear and angular head acceleration. The validity of this function was confirmed using the National Football League (NFL) head impact reconstructions in addition to the impacts used to generate the function. Using this risk function enhances the data analysis by increasing the importance of the higher acceleration impacts.

$$R(a, \alpha) = \frac{1}{1 + e^{-(-10.2 + 0.0433 * a + 0.000873 * a - 0.000000920 * a\alpha)}}$$

Once the risk is calculated, the risk is then multiplied by the exposure for a given configuration. Exposure is equivalent to one for whitewater activities because participants typically only undergo one major head impact annually (Spittler, et al., 2020). This is done for each testing configuration, and each value is then summated together to create the STAR value. The STAR value for each helmet is then used to determine its STAR rating. It is important to note that the STAR value is different from the star rating. Lower STAR values represent a lower risk of concussion and are then assigned to higher star ratings. The star rating ranges up to five stars for the best available helmets. Consumers are familiar with the star ratings



Figure 2: The front impact condition is shown on the right with the pendulum system.

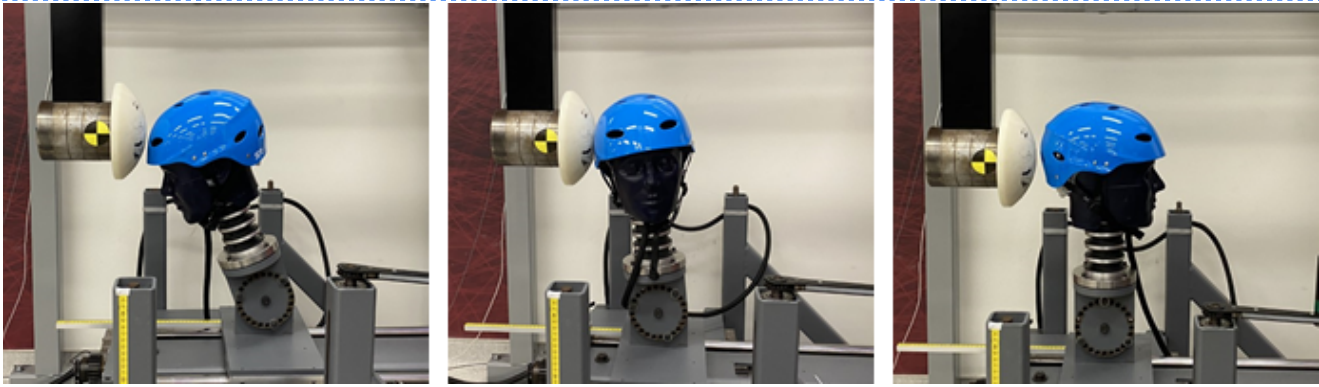


Figure 3: Front (left), side (middle), and rear (right) impact conditions.

Results

Higher linear acceleration values were observed for the front impact conditions, and higher rotational acceleration values were observed for the side impact conditions. The linear regression relating linear and rotational acceleration was strongly correlated ($r^2=0.71$). However, there was a low correlation between helmet price and STAR value ($r^2=0.11$), and there was also a low correlation between helmet mass and STAR value ($r^2=0.03$).

In the 3.1 m/s front impact condition the 21 helmeted tests resulted in a range of 30.2 – 131.2 g

and 1601 – 5036 rad/sec². In the 4.9 m/s front impact condition the 21 helmeted tests resulted in a range of 82.0 – 282.5 g and 4024 – 13069 rad/sec² (Figures 4 and 5).

In the 3.1 m/s side impact condition the 21 helmeted tests resulted in a range of 35.7 – 129.7 g, and 2500 – 3678 rad/sec². In the 4.9 m/s side impact condition the 21 helmeted tests resulted in a range of 88.1 – 316.4 g and 5609 – 24563 rad/sec².

In the 4.9 m/s rear impact condition the 21 helmeted tests resulted in a range of 82.9 – 332.0 g and 3336 – 14381 rad/sec². The helmets' STAR values resulted in a range of 0.2518 – 4.8634 (Figure 6).

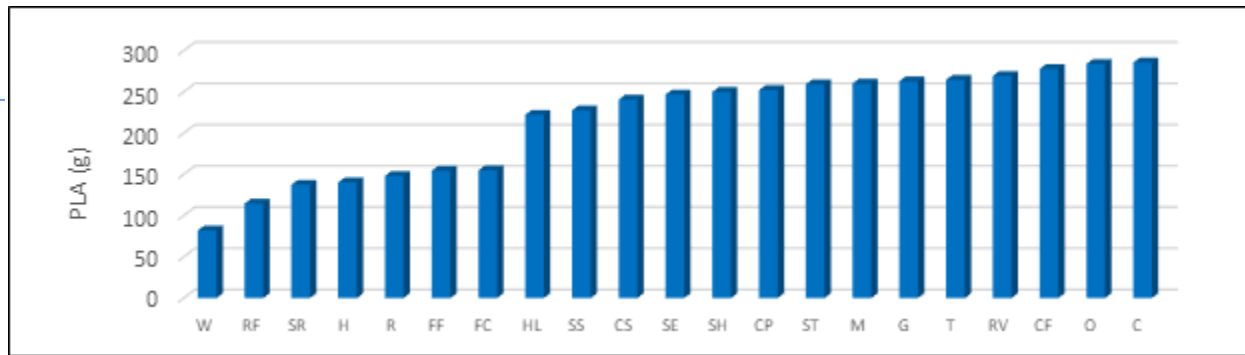


Figure 4: Peak resultant linear (PLA) head acceleration values (g) for the high speed of 4.9 m/s in the front impact direction. Sorted lowest to highest.

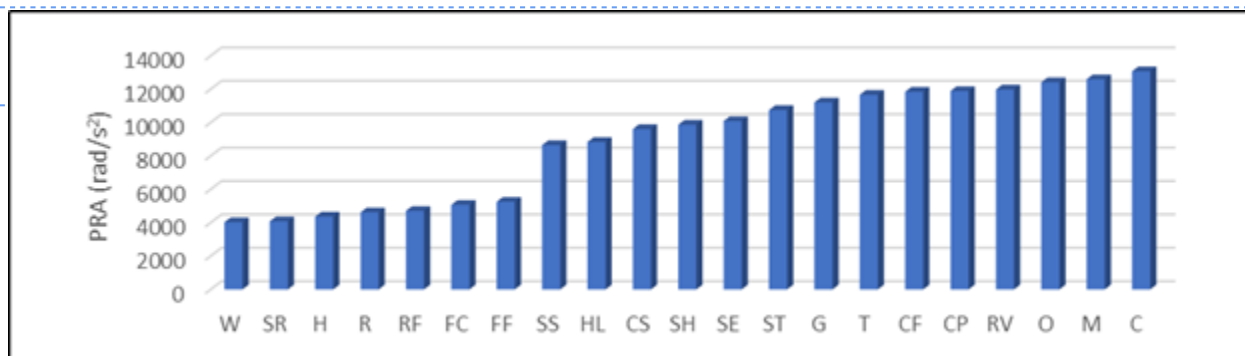


Figure 5: Peak resultant rotational (PRA) head acceleration values (rad/sec²) for the 4.9 m/s front impact condition. Sorted lowest to highest.

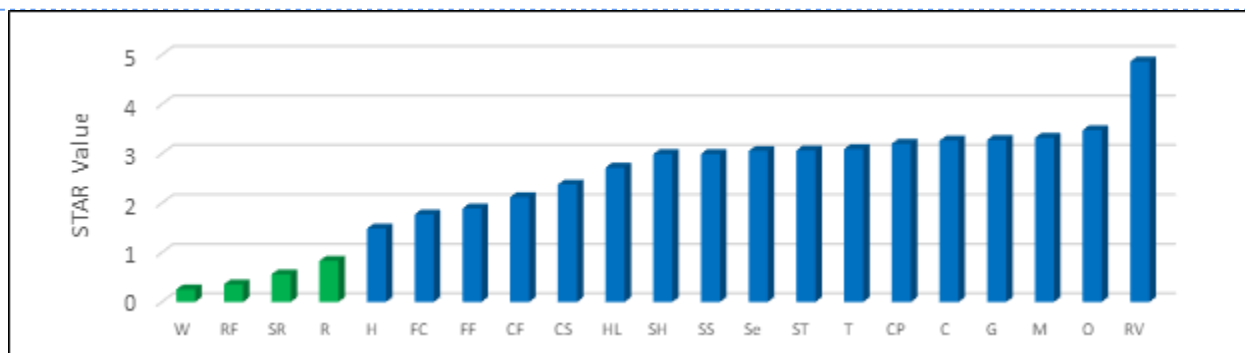


Figure 6: STAR values for each helmet with lower values indicating lower risk of concussion.

Discussion and Conclusions

The majority of the whitewater helmets performed poorly given that the STAR values observed for the helmets indicate an extremely high probability of concussion for each impact (Figure 6). The helmets should reduce head accelerations by

a far greater margin for lower concussion risks (Figures 4 and 5). For example, the STAR values over three indicate that for the six impact conditions over three concussions would be predicted. In contrast, the best helmets can reduce this value below one. In order to provide a useful tool for consumers to make informed decisions, the STAR

values for each helmet were used to create the star rating from five stars for the best helmet to one star for the lowest performing helmets (Table 2 and Figure 6). This is similar to how automobiles are rated up to five stars for consumers to easily understand the safety performance (Hershman, 2001). For this study, STAR values below 1.0 were assigned the highest five star rating as they indicate less than one concussion for all six impact conditions. STAR values between 1.0 and 2.0 were assigned four stars, and STAR values of 2.0 to 3.0 were divided between the three and two and one star ratings. Below the one star rating is the “not recommended” category, which means that the helmets performed so poorly that they are not recommended for purchase. The “not recommended” helmets have STAR values above 3.0, indicating a very high risk of concussion in over half of the six impact conditions.

Higher acceleration values for both linear and rotational acceleration were observed at higher impact speeds, with linear and rotational acceleration being strongly correlated ($r^2 = 0.72$). Linear acceleration was observed to be higher in the front impact conditions, whereas rotational acceleration was observed to be higher in the side condition. A possible cause for this observation is the difference in centric and non-centric aspects for each impact location.

Helmet performance did not correlate well with other factors such as weight ($r^2 = 0.03$) and price ($r^2 = 0.11$). This highlights the necessity of a helmet rating system, because consumers cannot always use these factors as an indication of helmet

performance. Moreover, all five of the manufacturers produced helmets that performed in the lowest “not recommended” category, while only one of the manufacturers, Sweet Protection, produced five star rated helmets.

These results are similar to what was observed with hockey helmets given that both whitewater helmets and hockey helmets performed very poorly on average (Rowson, et al., 2015). In contrast, other sports such as football have helmets that are all very high performing (Rowson & Duma, 2011). The whitewater helmets should reduce the head impact accelerations much more across all helmets. One method to accomplish this would be to mirror some of the technologies utilized to design the newer and more advanced football helmets (Bailey, et al., 2020).

Limitations

A limitation of this study is that only one size of helmet was tested. This assumes that performance is consistent throughout each size of helmet. However, there still could be deviation in performance as size increases or decreases. An additional limitation of this study is the assumption that there is no difference in male and female injury response by using one metric for both sexes (Solomito, et al., 2019). Future research could include testing with different sized helmets as well as considerations for potential concussion risk differences between males and females.

Manufacturer	Helmet Model	Price (\$)	STAR Value	Rating
Sweet Protection	Wanderer Helmet	149.95	0.25	5
Sweet Protection	Rocker Fullface Helmet	329.95	0.36	5
Sweet Protection	Sweet Rocker - Dagger Edition	259.99	0.56	5
Shred Ready	Rocker Helmet	229.95	0.83	5
Shred Ready	Halfcut Whitewater Helmet	99.95	1.49	4
Shred Ready	Fullcut Whitewater Helmet	110.00	1.77	4
Shred Ready	Fullface Whitewater Helmet	149.95	1.89	4
NRS	Chaos Full Cut Helmet	69.95	2.12	3
NRS	Chaos Side Cut Helmet	79.95	2.38	3
NRS	Havoc Livery Helmet	49.95	2.72	2
Shred Ready	Shaggy Helmet	179.95	2.99	1
Shred Ready	Super Scrappy Helmet	89.95	2.99	1

Shred Ready	SESH Helmet	54.95	3.06	N.R.*
Sweet Protection	Strutter Helmet	199.95	3.06	N.R.*
WRSI	Trident Composite	199.95	3.10	N.R.*
WRSI	Current Pro	139.95	3.20	N.R.*
WRSI	Current	119.95	3.26	N.R.*
Gath	Gath Gedi	189.00	3.28	N.R.*
WRSI	Moment Fullface	179.95	3.32	N.R.*
Shred Ready	Outfitter Pro Helmet	49.00	3.48	N.R.*
Gath	Gath RV	209.00	4.86	N.R.*

Table 2: All 21 helmet models related to their respective price, STAR value, and star rating.

*N.R. stands for Not Recommended.

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