Head Impact Conditions and Helmet Performance in Snowsports

Summer Keim

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Steven Rowson

Stefan Duma

Gunnar Brolinson

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ACADEMIC ABSTRACT

Mild traumatic brain injury in snowsports is a prevalent concern. With as many as 130,000 hospitalized injuries in the U.S. associated with snowsports in 2017, head injury constitutes about 28% and is the main cause of fatality. Studies have found that a combination of rotational and linear velocities is the most mechanistic way to model brain injury, but despite decades of research, the biomechanical mechanisms remain largely unknown. However, evidence suggests a difference in concussion tolerance may exist between athlete populations. To improve the ability to predict and therefore reduce concussions, we need to understand the impact conditions associated with head impacts across various sports. There is limited research on the conditions associated with head impacts in snowsports. These head impacts often occur on an angled slope, creating a normal and tangential linear velocity component. Additionally, the impact surface friction in a snowsport environment is highly variable, but could greatly influence the rotational kinematics of head impact. Currently helmet testing standards don't consider these rotational kinematics, or varying friction conditions that potentially occur in real-world scenarios.

The purpose of this study is to investigate the head impact conditions in a snowsport environment to inform laboratory testing and evaluate snow helmet design. We determined head impact conditions through video analysis to determine the impact locations, mechanism of fall, and the kinematics pre-impact. We used these data to develop a test protocol that evaluates snowsport helmets in a realistic manner. Ultimately, the results from this research will provide snowsport participants unbiased impact data to make informed helmet purchases, while concurrently providing a realistic test protocol that allows for design interventions to reduce the risk of injury.

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GENERAL AUDIENCE ABSTRACT

Mild traumatic brain injury in snowsports is a prevalent concern. With as many as 130,000 hospitalized injuries in the U.S. associated with snowsports in 2017, head injury constitutes about 28% and is the main cause of fatality. Studies have found that a combination of rotational and linear velocities is the most mechanistic way to model brain injury, but despite decades of research, the biomechanical mechanisms remain largely unknown. However, evidence suggests a difference in concussion tolerance may exist between athlete populations. To improve the ability to predict and therefore reduce concussions, we need to understand the impact conditions associated with head impacts across various sports. There is limited research on the conditions associated with head impacts in snowsports. These head impacts often occur on an angled slope, creating a normal and tangential linear velocity component. Additionally, the impact surface friction in a snowsport environment is highly variable, but could greatly influence the rotational kinematics of head impact. Currently helmet testing standards don't consider these rotational kinematics, or varying friction conditions that potentially occur in real-world scenarios.

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INTRODUCTION

Mild traumatic brain injuries, also known as concussions, are a growing health concern. Research estimates that as many 3.8 million sports-related concussions occur each year in the United States.[1, 2] While concussions were once considered to result in only transient symptoms and neurocognitive impairment, recent research has raised the possibility of links between repetitive concussions and long-term neurodegeneration.[3-6] Within snowsports, the prevalence of head injury is high, with as many as 130,000 hospitalized injuries in the U.S. associated with snowsports in 2017,[7] head injury constitutes about 28% and is the main cause of fatality.[8-10]

Research has found that concussion is predominantly caused by shearing of the brain tissue which is a result of both rotational and linear velocities.[11-13] Growing evidence indicates a difference in concussion tolerance between athlete populations,[14, 15] so to mitigate brain injuries, we need to understand the impact conditions associated with head impacts across sport types.

One method to characterize the kinematics associated with concussion has been to observe head impacts in high-risk sports.[16-19] Within snowsports, there are limited studies of head impacts or reconstructions of real-world crash events.[20-24] One study analyzed a single head impact using video and model-based image-matching to obtain 3-D kinematics and reconstruct the fall in a laboratory setting.[20, 25] However, this lengthy process produced only one datapoint. Another study analyzed 9 head impacts to determine if the pre-impact velocities were higher than helmet testing requirements, but did not translate this real-world data to a laboratory test.[21, 22] Multiple studies analyzed various impacts conditions with helmets, but did not use real-world data to inform their testing.[23, 24]

In snowsports head impacts often occur on an angled slope,[26] which creates both a tangential and normal component to the resultant linear velocity. The relative contribution of these component velocities in snowsport head impacts are unknown but could greatly affect the amount of force put on the helmet upon impact. For snowsport athletes traveling at high velocities down an angled slope, reducing the impact-induced rotational kinematics is key to decreasing the risk of brain injury.[27] Snowsport crashes occur on snow or ice which vary in their friction and hardness. However, the effects of surface friction differences on head rotation are unknown.

Currently, all snow helmets are required to pass two testing standards: the American ASTM 2040 and the European CE EN 1077. These pass/fail standards do not indicate of which helmets reduce risk better than others and only test the protective capabilities of helmets under specific impact conditions. They don’t consider rotational kinematics, tangential velocities, or different friction conditions that potentially occur in real-world scenarios.

Therefore, there is a great need to understand the conditions surrounding head impacts in snowsports. If the fall mechanisms, impact locations, effects of friction, and head kinematics are known, test protocols can be developed that accurately simulate real-world scenarios. This could result in realistic evaluation methods that could assess if helmets are protecting against brain injury on the slopes. The purpose of this study is to understand the head impact conditions in a snowsport environment and use the data to inform laboratory testing to evaluate current snow helmet design.

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CHAPTER 1

The Effect of Impact Surface Friction on Snow Helmet Performance during Oblique Impact Testing

ABSTACT

Snowsports, although a popular winter activity, is associated with a high amount of risk. Up to 130,000 hospitalized injuries occur each year in the U.S. alone. Many of those injuries are to the head, which is the leading cause of snowsport-related fatality. While helmets are effective at reducing injury risk, helmet use has been highly variable. Recent improvements in snow helmet design have included integrating the Multi-directional Impact Protection System (MIPS), a slip-plane layer between the head and helmet to reduce rotational head kinematics resulting from impact. MIPS is often tested in bicycle helmet impact scenarios, where the head impacts a rough surface intended to simulate a road surface. However, in snowsports, the head often impacts snow or ice. This study aimed to investigate the effect of different impact surface friction conditions when testing ski helmets with and without MIPS. Tests involved dropping a helmeted headform onto an oblique anvil using a drop tower. The anvil's friction was varied using either 80-grit sandpaper to simulate a high-friction condition or bare steel to investigate a lower friction condition. A total of 10 different helmet models were tested, including 5 with MIPS. Each of the helmets were dropped at two locations, rear boss and side. Resultant peak linear acceleration (PLA) and peak rotational velocity (PRV) were calculated for each test. The higher friction condition corresponded to higher PLA. Whereas for PRV, higher friction resulted in a lower PRV. It was observed that the lower friction surface caused head rotation in the opposite direction of what was seen with the higher friction surface. MIPS did not influence PLA but affected PRV to varying

degrees depending on impact condition. This study's limitations include a small sample of helmet types, testing at a single velocity, and friction conditions were simulated with sandpaper and bare steel. Future work should include testing more helmet models over a larger velocity range in better simulated snow and ice conditions.

INTRODUCTION

Snowsports have provided an enjoyable wintertime activity worldwide for many decades. More than 22.5 million people in the U.S. participated in snowboarding or skiing during the 2017-2018 season.[1] However, this wintertime activity is not without risk; as many as 130,000 hospitalized injuries in the U.S. were associated with snowsports in 2017.[2] Of those injuries, head injury constitutes about 28% and is the main cause of fatality.[3-5] Further, mild traumatic brain injury, or concussion, accounts for 11% of all injuries experienced by skiers and snowboarders.

Helmet use in snowsport activity was low until the early 2000s. A surveillance study conducted on 28 U.S. ski resorts found that only 12% of participants wore a helmet in 2001.[6] In 2019, the prevalence of helmets on the slope had increased to approximately 75%.[7, 8] Further contributing to the low compliance, the effectiveness of snow helmets to protect against brain injury is a controversial subject. Some research suggests that snow helmets have no effect in protecting against brain injury.[9, 10] Other researchers theorize that helmets contributed to injuries by promoting risky behavior or increasing cervical spine injury. Continued research proved these assumptions false.[8, 11-13] Overall, research demonstrates that helmets decrease head injuries.[11, 14-17]

Traumatic brain injury is predominantly caused by a combination of rotational and linear accelerations.[18-23] In snowsports, head impacts often occur on an angled slope rather than a flat surface and traveling at high speeds when they fall,[24] making the rotational aspect of specific importance. Therefore, reducing the impact-induced rotational kinematics is key to further reducing brain injury risk for snowsport athletes.[25] Recent advancements in snow helmet design have tried to address this issue by including Multi-directional Impact Protection System (MIPS AB, Täby, Sweden) technology. MIPS is a patented helmet insert that creates a slip-plane layer between the wearer's head and the rest of the helmet. This layer is intended to reduce rotational head kinematics resulting from impact, thereby, decreasing the risk of brain injury.

MIPS has been proven effective for bike helmets in some impact scenarios.[26-28] Similar to snowsport helmets, bike helmets are tested on oblique surfaces. This is because these impacts often occur while experiencing a forward motion during the fall. As opposed to a flat surface, an angled impact surface allows for the drop velocity to be converted into two velocity vectors: a tangential (forward) vector and a normal (downward) vector. The impact surface for bike crashes is typically rough, such as concrete, gravel, or asphalt. Therefore, oblique bicycle helmet testing typically uses 80-grit sandpaper with a 0.5 coefficient of friction to simulate an asphalt road surface when evaluating helmet performance.[29] Such testing has shown MIPS to reduce angular velocity changes in bike helmets.[26] These high friction surfaces tend to "grab" the helmet shell.

In contrast to cycling head impacts, snowsport impacts occur on snow or ice, both of which have much lower friction coefficients. The effects of surface friction differences on head rotation are unknown. The purpose of this study was to determine how snow helmet impact performance differs in high- and low-friction conditions.

METHODS

A drop tower was used to evaluate snowsport helmets at different impact locations and friction conditions. The drop tower consisted of a falling support ring that guided a headform to impact and angled anvil. The support ring for the helmeted head consisted of 5 rods that were independently adjusted to achieve each specific impact location. The head was held in place by a lever arm that released just before impact. A dual-axis inclinometer was used to position the headform consistently. Three linear accelerometers (Endevco 7264B-2000, Meggitt Sensing Systems, Irvine, CA), as well as a triaxial angular rate sensor (ARS3 PRO-18K, DTS, Seal Beach, CA) were mounted at the headform's center of gravity.

The tests were conducted using a medium National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform. This headform was chosen because of its realistic shape, biofidelic impact response, and lower surface friction than the Hybrid III.[30-32] Whether to include a neck and effective torso mass during drop tests is a debated subject. Dropping only a head without a neck has been shown to have a biofidelic impact response. Adding a neck can reduce biofidelity for certain impact scenarios that cause the neck to undergo considerable axial loading. The neck has been shown to behave differently than a human neck under axial load due to its overly stiff response and elastic characteristics that store energy.[33, 34] Thus, under the vertical impact conditions considered in this study, a neck may not represent a human response. A recent study using oblique drop tower testing demonstrated that the neck affected the head's impact response by decreasing PLA and PRA, and it also was associated with higher variance.[31] Furthermore, the inclusion of the neck did not have the same effect on all impact scenarios. To be consistent with current bicycle helmet test systems, we chose not to include a neck attached to a falling mass.

Snowsport helmet test standards require a helmeted headform to be dropped onto a flat anvil at linear velocities ranging from 5.42 m/s to 6.8 m/s. Under these velocities, the headform must not exceed a peak linear acceleration of 250 g to 300 g.[35] In this experiment, the helmeted headform was dropped onto an oblique anvil of 45° to produce normal and tangential impact velocities more representative of real-world impacts.[36] The helmets were dropped at a 5 m/s resultant velocity, which consisted of a 3.55 m/s normal velocity and a 3.55 m/s tangential velocity. The resultant velocity was measured for each test using a light gate to verify impact velocities. Impact velocities were within ± 0.15 m/s of the target value.

The helmets were dropped to impact the oblique anvil at two locations, based on the most common injury mechanisms that have been observed in skiers and snowboarders (Figure 1.1).[24] The first location (rear boss) simulated a backward fall, or “backslap.” This was positioned to impact the occipital region slightly to the right of the midsagittal plane. The second location (side) simulated a sideways fall or “catching an edge” and was positioned to impact the parietal region.

Figure 1.1: Snowsports helmets were tested at two impact locations, rear boss (left) and side (right). Helmets were dropped onto an oblique anvil of 45° under two friction conditions (low and high).

Ten different helmet models were tested, two from each model for a total of 20 helmets. Brands included Lucky Bums, Wildhorn, Giro, Smith Optics, Oakley, POC, Pret, and Sweet Protection (Table 1.1). The helmets ranged in price from $50-$250 to encompass the large spectrum of helmets individuals might purchase based on income or skill level. Five helmets included MIPS.

Table 1.1: Helmet models used in testing. Five included MIPS in the design. The price range varied according to model and the inclusion of MIPS.

Helmet Model	**MIPS**	**Price**
Lucky Bums	No	$47
Wildhorn Drift	No	$80
Giro Nine	Yes	$120
Giro Seam	No	$160
Giro Ledge	Yes	$90
Smith Optics Holt	No	$70
Oakley Mod 5	Yes	$138
POC Receptor Bug	No	$120
Pret Cynic X	Yes	150
Sweet Protection Switcher	Yes	250

The effect of impact surface friction on MIPS was evaluated by varying the friction of the oblique anvil's surface. For the higher friction condition, 80-grit sandpaper was used (0.5 coefficient of friction) following ECE R-22.05 motorcycle helmet testing requirements.[29] To simulate the snow/ice condition, bare steel was used. The static coefficient of friction for polytetrafluoroethylene (PTFE), a material used in some helmets, on snow is 0.05.[37] This is within the range of PTFE on bare steel, 0.05-0.2.[37] Therefore, using bare steel and 80-grit sandpaper makes two distinct friction conditions that allow effective comparison of friction effects.-

40 drop tests were performed on the 10 different helmet models at the two locations with the two friction conditions. Each helmet was impacted a total of two times, once on each impact location.

Its matched pair was also dropped at the same two locations but under the other friction condition. For each high friction test, a new piece of adhesive-backed 80-grit sandpaper was applied to the anvil. Between trials, the anvil was cleaned and all residue from the sandpaper removed, not to affect the lower-friction bare-steel condition.

Linear acceleration and rotational velocity data were collected at 20 kHz for each test. The kinematic data were filtered 4-pole phaseless Butterworth filters of channel frequency class 1000 for linear acceleration and 175 for rotational velocity. Resultant peak linear acceleration (PLA) and peak rotational velocity (PRV) were calculated for each test. The data were analyzed through a mixed-effects ANOVA model with the three factors: impact location, friction condition, and MIPS with the random effect of helmet model (RStudio, V 1.4.1106, Inc., Boston, MA). A least square means pairwise comparison with a Tukey adjustment (at 95% confidence level) was also computed.

RESULTS

Peak linear acceleration and peak rotational velocity differed depending on friction condition. The average PLA was 126.1 ± 25.3 g. The greatest PLA was 187.9 g which was a side high-friction impact. The lowest PLA was 78.0 g which was a rear boss low-friction impact. The average PRV was 17.33 ± 5.46 rad/s. The maximum PRV was 27.06 rad/s at the side location with low friction. The minimum PRV was 3.81 rad/s at the side impact location with high friction.

Friction ($p < 0.0001$) and location ($p = 0.041$) were significant factors on PLA. MIPS had no effect on PLA ($p = 0.591$), however, the interaction between MIPS and friction was significant ($p = 0.046$). Higher friction was associated with a higher PLA, but the extent to which it increased PLA depended on the location (Figure 1.2). The high friction condition increased PLA by 30.0 g at the rear boss location. This effect was more substantial in the helmets without MIPS (p=0.0013, CI = [20.3, 50.0]), than with MIPS (p = 0.0371, CI = [10.0, 39.8]). At the side location, the high friction increased PLA by 28.7 g. This effect was more notable in the helmet models without MIPS (p = 0.0002, CI = [25.1, 54.9]) than models with MIPS (p = 0.1498, CI = [5.1, 34.9]).

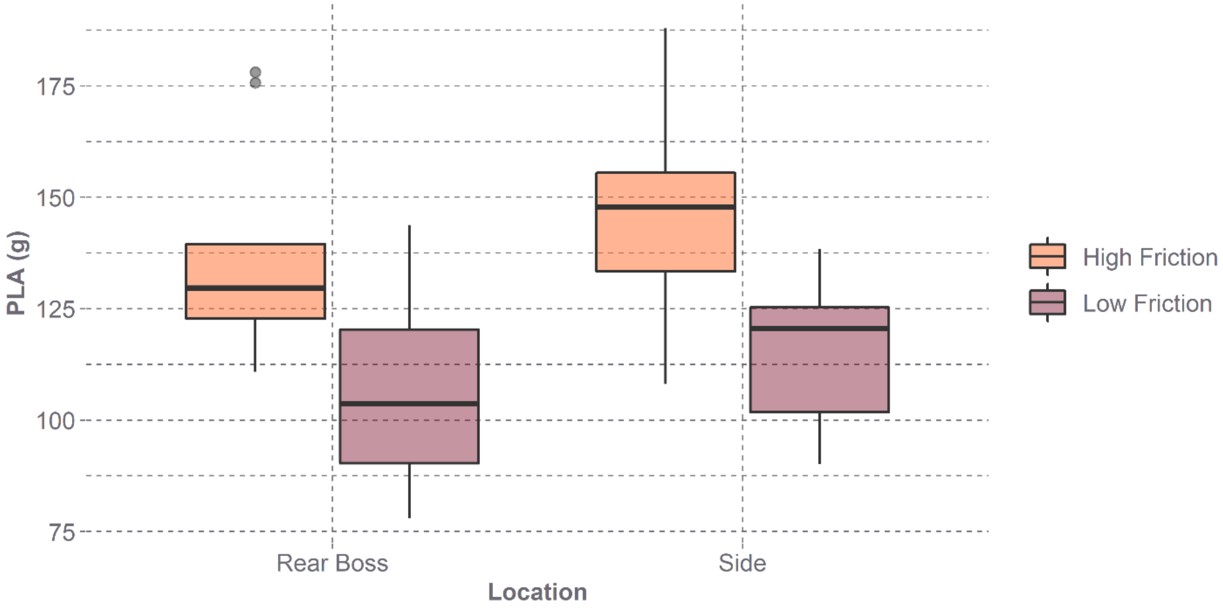

Figure 1.2: The effect of friction on linear acceleration. At each location, the high friction condition increased PLA. At each location, the high friction condition increased PLA.

All three factors, MIPS (p = 0.0447), location (p = 0.0014), and friction (p = 0.00029) influenced PRV, as well as the location-friction interaction (p = 0.001). The extent to which friction decreased rotational velocity varied by MIPS and impact location (Figure 1.2).

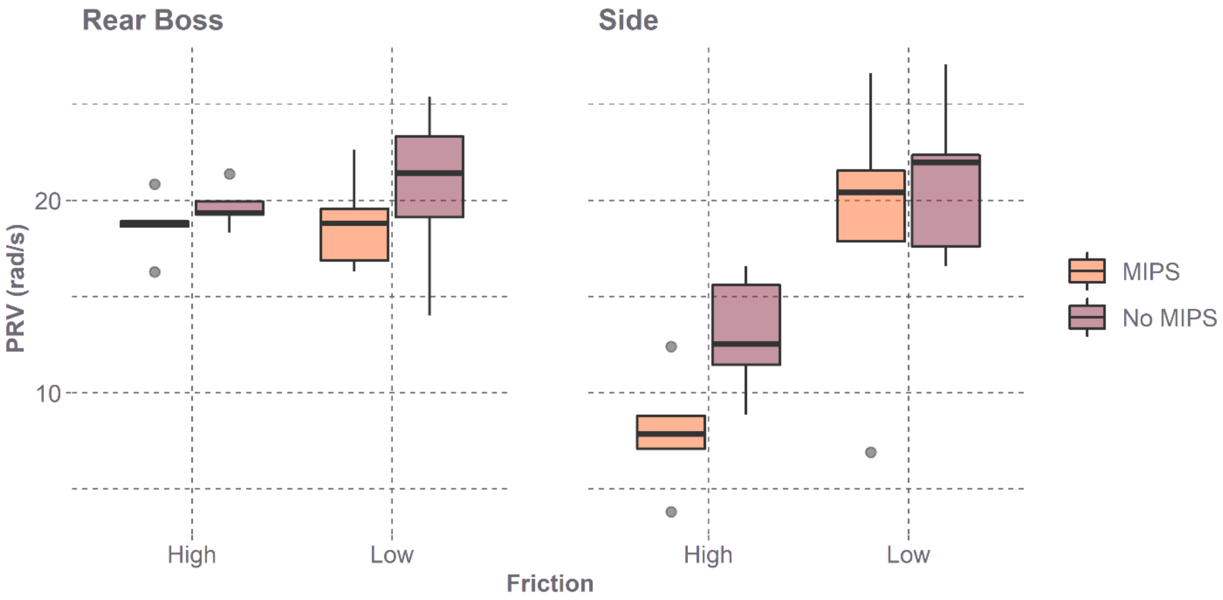

Figure 1.3: The effect of friction on rotational velocity. At each location, the low friction condition increased PRV while the presence of MIPS decreased PRV.

At the rear boss location with MIPS, friction was not found to be significant, which was also true for rear boss without MIPS. However, at the side location, friction did have a significant effect with MIPS, and without MIPS (Table 1.2).

When controlling for location and friction, MIPS was not shown to have a significant effect. At the rear boss location, MIPS reduced PRV by 0.95 rad/s with high friction and by 1.82 rad/s with low friction. For side impacts, MIPS reduced PRV by 2.36 rad/s with high friction and by 2.44 rad/s with low friction (Table 1.2).

Impact location was found to influence PRV under the conditions of high friction with the inclusion of MIPS. However, without the inclusion of MIPS, this effect was reduced. Under low friction conditions, the impact location had no effect either with MIPS or without MIPS (Table 1.2).

Table 1.2: Contrasts for each condition on PRV with significance level and confidence intervals.

Control Condition	Control Condition	Varied Condition	Significance (pvalue)	Confidence Interval
Rear boss	MIPS	Friction	1.0	[-5.19, 4.92]
Rear boss	No MIPS	Friction	0.9	[-6.06, 4.06]
Side	MIPS	Friction	0.0044	[-15.74, -5.63]
Side	No MIPS	Friction	0.0496	[-13.17, -3.06]
Rear boss	High friction	MIPS	0.9999	[-4.24, 6.14]
Rear boss	Low friction	MIPS	0.9948	[-3.37, 7.0037]
Side	High friction	MIPS	0.4679	[0.01, 10.02]
Side	Low friction	MIPS	0.9713	[-2.56, 7.45]
High friction	MIPS	Location	0.0043	[5.67, 15.77]
High friction	No MIPS	Location	0.1652	[1.60, 11.71]
Low friction	MIPS	Location	1.0	[-4.89, 5.22]
Low friction	No MIPS	Location	1.0	[-5.52, 4.60]

DISCUSSION

This study evaluated the effect of friction on helmet performance. Helmet performance was evaluated through the metrics peak linear acceleration and peak rotational velocity which are predictors of brain injury. We found that an increase in friction raised PLA. Analyzing high-speed video frames of the impact event (Figure 1.4) shed light on this increase. In high-friction conditions, the helmets impacted the anvil and then bounced off slightly upward, which caused a greater change in velocity. However, in the low-friction condition, the helmets continued to slide down off the anvil after impact, resulting in a lower change in linear velocity. These differences in velocity change explain the differences in acceleration.

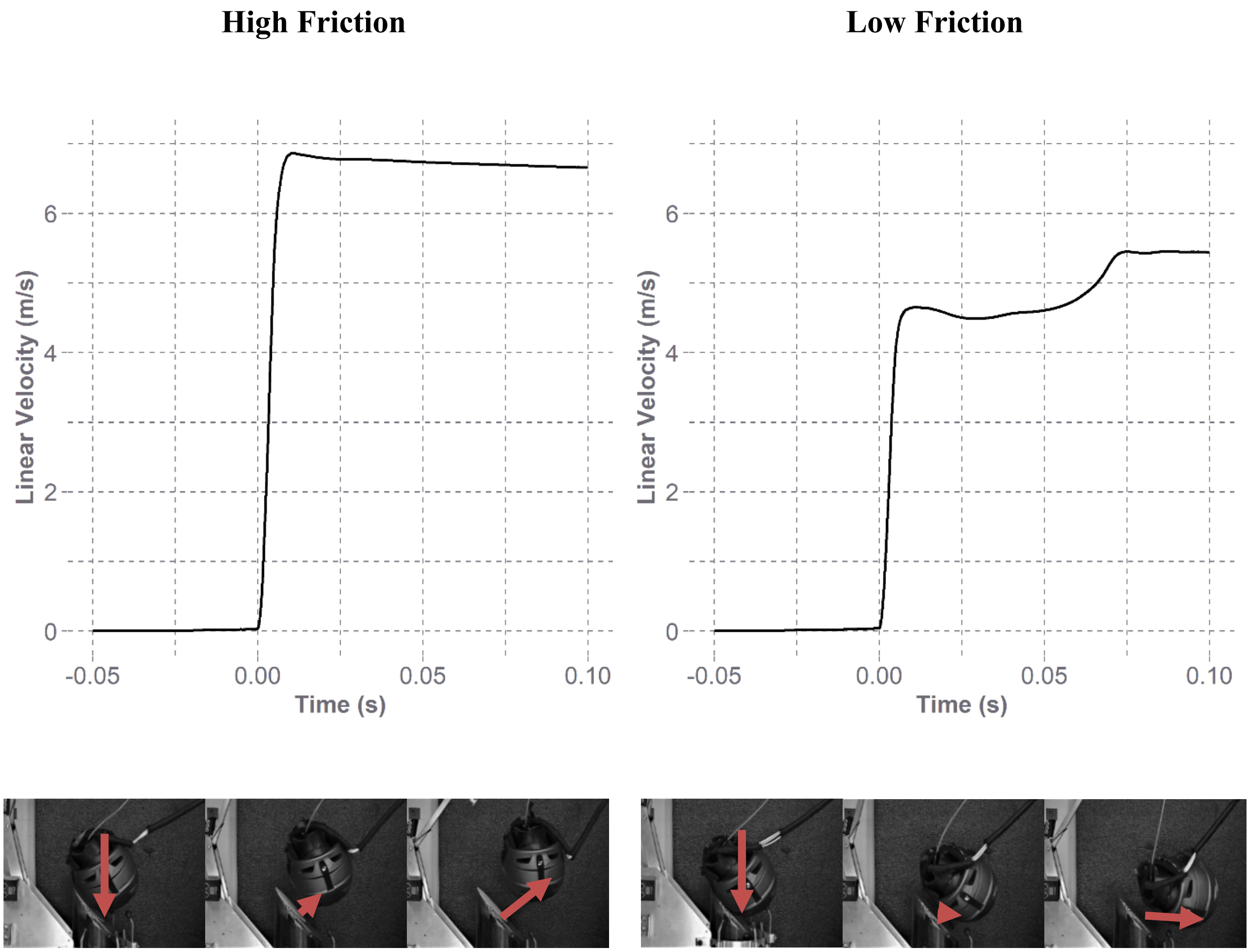

Figure 1.4: High speed video frames of two exemplar side impacts. The low friction condition (right) reduced PLA because the helmet slid down the anvil, causing a lower velocity change.

For rotational velocity, a higher friction impact surface reduced PRV. The reason for this phenomenon was also determined from visual analysis of high-speed video frames (Figure 1.5). In the high-friction condition, the anvil grabbed the helmet shell rotating it clockwise (CW) off the anvil. Alternatively, for the low-friction condition, the head slid off the smooth anvil rotating counter-clockwise (CCW). This caused a greater rotation in the opposite direction of the high friction condition.

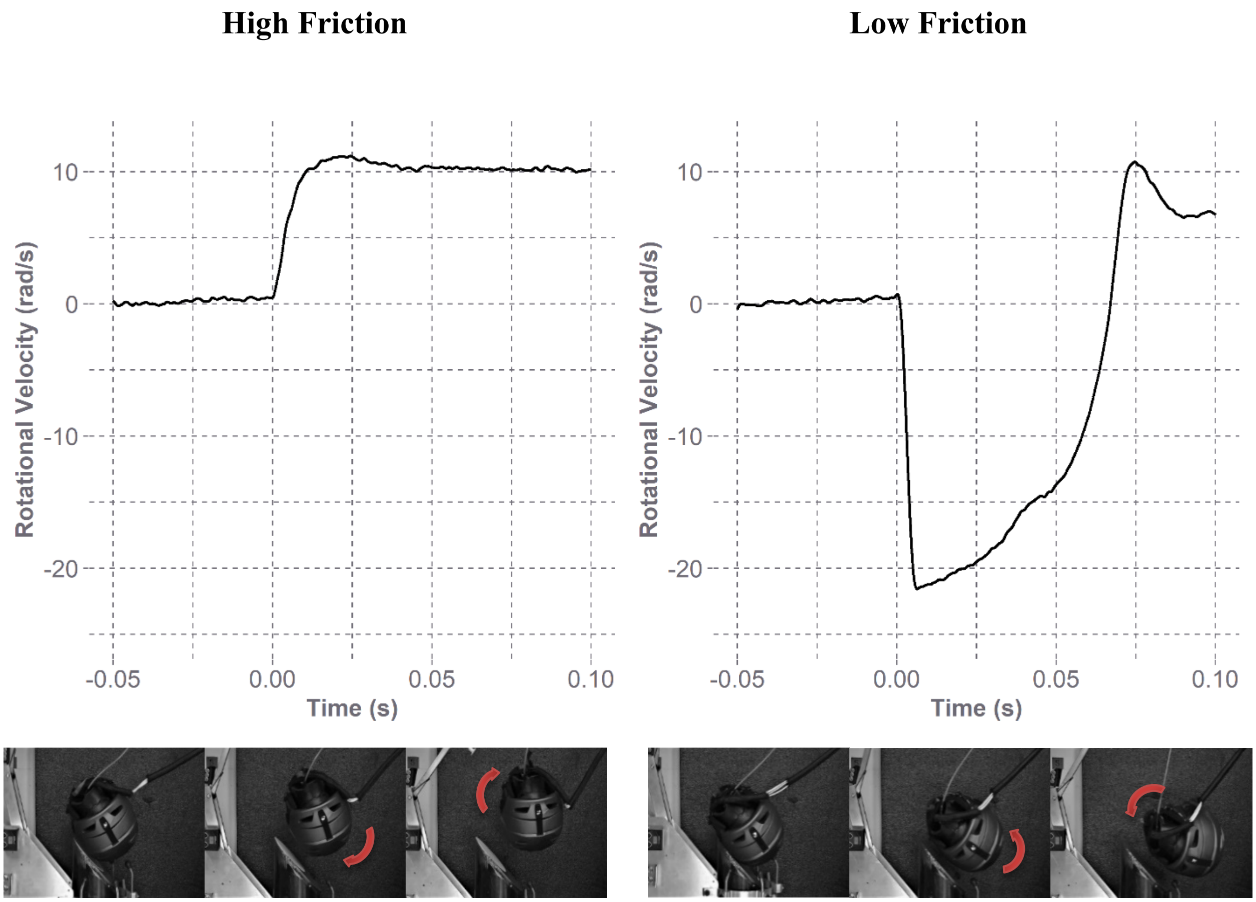

Figure 1.5: High speed video frames of two exemplar side impacts. The low friction condition (right) increased PRV because the surface did not grab the helmet shell, causing greater rotation in the opposite direction.

This change in rotation direction was also observed in a previous study using a similar testing method.[38] In the high-friction condition, the larger frictional forces were large enough to overcome the downward normal force and rotate the headform CW, whereas the low friction surfaces resulted in a CCW rotation.

While MIPS did not influence PLA, it had a small effect in reducing PRV. A previous study, which used similar methods, found that MIPS was effective in reducing PRV (11%-14%) and marginally effective in reducing PLA ($p < 0.01$).[26] More recent studies on bike helmets agreed with our findings. MIPS did not affect linear acceleration but significantly reduced rotational acceleration by 21-44% and rotational velocity by as much as 67% across all impact scenarios.[27]

Friction was found to be an important component for testing snowsport helmets. It had a notable affect increasing PLA and reducing PRV so should be considered in the testing of snow helmets. To be representative of real-world conditions, the impact surface in snow helmet testing should approximate the friction of snow or ice.

This study had several limitations. Only 10 helmet models were tested and are not likely representative of the performance range of all snowsport helmets. Furthermore, low- and high-friction conditions were simulated with sandpaper and steel. Therefore, helmet impacts did not fully match actual impacts in snowy or icy conditions. However, two distinct friction conditions were investigated. Lastly, these helmets were tested at a single velocity (5 m/s). However, in real-world scenarios, snowsport participants are likely traveling at much higher and over a broader range of speeds. Future work should include testing additional helmet models over a large range of velocities with real snow and ice to be more representative of real-world crashes.

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CHAPTER 2

Video-Based Analysis of Head Impacts in Snowsports to Understand the Associated Kinematics

ABSTRACT

This research studies the head impacts in a snowsport environment to understand the common impact locations and the associated kinematics pre-head impact. Specifically, we worked with the men's and women's U.S. Ski and Snowboard Team to characterize the boundary conditions of head impact during high-risk event through video analysis. The videos came from two different sources, retrospective and prospective collection. The retrospective component came from broadcast video of previous competition events, while the prospective videos were taken by our own research personnel during the 2019-2020 competition season. The varying quality of the videos created unique analysis techniques to extract reliable data. However, both approaches used a calibration object to determine the pixel space, then the pre-head impact velocities were extracted from video using the frame rate and the distance the athlete traveled down the slope. Rear boss impacts produced the highest resultant velocity (8.23 m/s), followed by back impacts (6.08 m/s). Side impacts (4.97 m/s) and front impact (4.73 m/s) had similar resultant velocities. All of the head impacts had a much higher tangential velocity than normal velocity. The impact location with the highest normal component was the back of the head. This was also the location that was hit most often at 44%. Athletes impacted the side location 25% of the time, rear boss location 19%, and front 13%. There was inherent error associated with this technique which could mostly be attributed to the fact that any point selected within the video frames was left up to the observer's discretion. Also, there was still slight movement between frames after background stabilization in the retrospective videos. One limitation is that it simplified

the 3-D movement of the athletes to x and y directions only. The small sample size used in this study could have produced bias in the results so cannot be generalized to the whole snowsport population. Future work would include taking video of more snowsport head impacts over a broader range of snowboarding and skiing events to better understand the common head impact locations and pre-impact velocities within the snowsport population. However, the results of this study have increased our understanding of head impact conditions in a snowsport environment through establishing video-based analysis techniques.

INTRODUCTION

Mild traumatic brain injuries, or concussions, are a growing health concern. Emergency department visits for concussion increased 62% between 2001 and 2009, and research estimates that as many 3.8 million sports-related concussions occur each year in the United States.[1, 2] While concussions were once considered to result in only transient symptoms and neurocognitive impairment, recent research has raised the possibility of links between repetitive concussions and long-term neurodegenerative processes.[3-6] Such reports have increased awareness and media attention on the potential health risks of concussion. Snowsports, a popular wintertime activity with more than 22.5 million people in the U.S. participating each year,[7] is also associated with concussion with as many as 130,000 hospitalizations due to snowsports every year.[8] Head injury constitutes around 28% of injuries experienced by snowboarders and skiers and the main cause of fatality,[9-11] with concussion specifically accounting for 11%.

With head injury occurring with such prevalence in snowsports, there is surprisingly little data on the conditions associated with these head impacts. Limited studies of have examined head impacts in snowsports. One study analyzed a single head impact using video from four camera views.[12] They then recreated a 3D computer model of the scene and used a model-based image-matching approach[13] to reconstruct the crash. From this they obtained the 3D kinematics to replicate the crash in a laboratory setting. However, this lengthy process produced only one data point. Another study viewed 9 head impacts using one camera view. This method utilized low-speed surveillance videos with a sagittal view of the head impact. With motion analysis software and the length of the skis for calibration, the 2-D kinematics of the impact were estimated. However, the increased ease of processing gave less informative results. The velocities were limited to the x and y directions only, and no rotational kinematics were found.[14, 15]

There is a great need to understand the conditions surrounding head impacts in snowsports. These impacts conditions are crucial to helmet testing. If the fall mechanisms, impact locations, and head kinematics are known, test protocols can be developed that accurately simulate these real-world scenarios. This could result in realistic evaluation methods that could assess if helmets are protecting against brain injury on the slopes.

The purpose of this study is to understand the conditions associated with head impacts in a snowsport environment to inform future helmet evaluation. We will observe head impacts in snowsports and procure data on how snowsport athletes impact their heads. This will be accomplished by actively collecting video data of impact events. Snowsports such as aerialists and freestyle will be chosen as the likelihood of head impact is greater in these high-risk events. We will also be collecting public video of historical ski crash events. This will give two sets of data sources, prospectively videos, collected by our research personnel, and retrospective videos, collected previously by news broadcasters, which will increase our dataset and enhance the validity of our results. These videos will then undergo an in-depth analysis process, to obtain the head kinematics of each skier pre-impact. The kinematics found from video will provide a baseline for what velocities skiers and snowboarders typically experience during head impact.

METHODS

To analyze real-world head impacts, initially an analysis approach had to be established that could effectively obtain kinematics from video. This includes the velocities and accelerations than a person might experience pre-head impact. To accommodate for the diverse video sources that would be collected, this video analysis approach had to be altered by varying degrees for each type.

Ultimately two different methods were used: one for the retrospective videos and one for the prospective videos. The retrospective videos used video stabilization and object tracker technology to obtain kinematics. The prospective events also obtained kinematics from object tracking, but used a more precise calibration method and had no need of video stabilization due to their higher quality.

Retrospective Video

The retrospective videos were provided by U.S. Ski and Snowboard. These were a compilation of broadcast videos from previous competition events from 2016-2019. Any crashes that occurred with a U.S. ski or snowboard athlete was extracted and saved onto the computer. These were then selected for future analysis by certain criteria. The selection process included evaluating the quality of video, and whether or not the crash resulted in a head impact. If head impact occurred, the head must be in plain sight, not obscured by snow or miscellaneous objects, and the athlete must be traveling perpendicular to the camera view.

The analysis process for each video initially started with importing the video into Adobe After Effects (AE). The video was then trimmed to a 3 second clip that solely included the fall. The Mocha Pro plugin within AE was used to stabilize the video. This removed any panning, tilting, or zooming that occurred while taking the shot and created a stationary background. After stabilization, the video was then imported into Tracker, a video software program that tracks an object within a calibrated video to compute its kinematics.

To calibrate the retrospective videos, the athlete's helmet was used. Medium-sized snow helmets have a circumference of 60 centimeters on average. From this, we calculated the diameter to be approximately 20 centimeters. Using this value, the video was calibrated in the frame before head impact using the width of the athlete's helmet. The width was defined as the shorter diameter of the helmet (i.e. when the athlete was looking straight at the camera). The length was defined as the longer diameter of the helmet (i.e. when the athlete was facing perpendicular to the camera). If the head was turned so that the width of the head was not visible in the frame before impact, three-fourths of the length of the helmet was used instead.

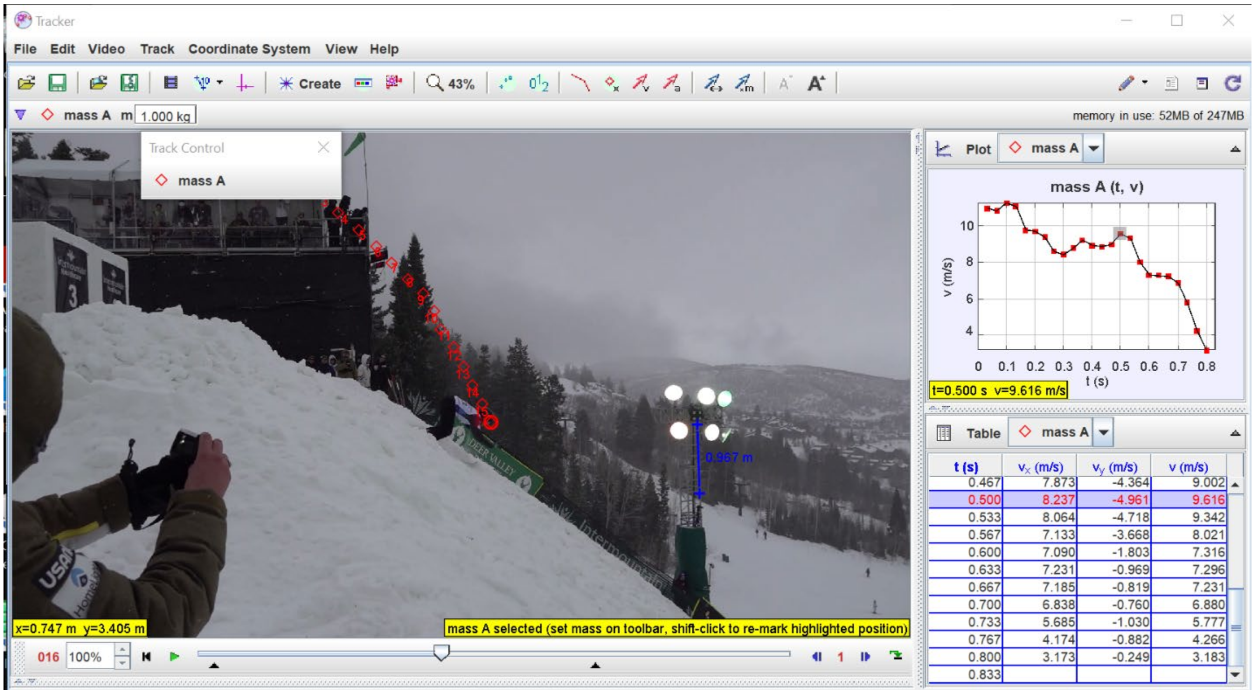
The athlete was then tracked through the video, frame-by-frame, until head impact occurred by selecting the center of the head in each frame (Figure 2.1). On a calibrated video, tracking the head gave a relative distance that the athlete traveled down the slope. Because the video was taken at a roughly 90-degree angle, perpendicular to the athlete, the movement of the athlete was simplified to only x and y directions. The positive x-axis within tracker was placed going down the slope and the positive y-axis was extending perpendicularly upward from the slope. Each of the retrospective videos had a frame rate of 29.97 frames per second. Therefore, using the time between frames of 0.033 seconds and the distance the athlete traveled, based on their center of head movement, the velocity pre-impact could be determined within Tracker. The resultant velocity was calculated from the x-velocity and the y-velocity. The velocities 5 frames before head impact were exported from Tracker and averaged to find the average velocities pre-head impact. This process was done for each retrospective video.

Prospective Video

The prospective videos from the Deer Valley, Utah, and Bristol New York competition events had a simpler analysis process for several reasons. They were shot using camcorders that take high-speed video of 119.97 fps with 3840 x 2160 resolution (Sony FDR-AX700 4K Camcorder). These videos used on-site calibration. Furthermore, the camcorders were set on stationary tripods, allowing for a stable background without any panning, zooming, or tilting of the camera. This allowed for the videos to be analyzed without the video stabilization process.

Two competition events were recorded with this method; one in Bristol, New York and another in Deer Valley, Utah. Using one camera, the U.S. ski and snowboard aerialists were recorded during the pre-competition practice runs. The camera was positioned perpendicular to the athletes so that the athletes could be tracked down the slope. After the videos were recorded, they were saved onto a computer. Any video that captured a head impact was selected for kinematic analysis.

The video analysis process was similar to the retrospective except for one key component, the calibration. For the prospective videos, this consisted of using a checkered rectangular board with a known length, width, and distance between points. The calibration board was held at arm's length and walked across the slope towards a camcorder recording high-speed video. This calibration video was then imported into Adobe AE as a sequence of calibration images. The crash videos could then be calibrated by matching the position where the athlete impacted the ground to a calibration image where the calibration board had the same location on the slope as the athlete. The length and width of the calibration board, as well as the distance between points, were used to determine the number of pixels that comprised one centimeter. Through determining the pixel-to-centimeter ratio, the image space could be found. This calibration process was done separately for each prospective video, as the position where the athlete hit the ground varied across impacts.



mass A selected (set mass on toolbar, shift-click to re-mark highlighted position)

t (s)	v_x (m/s)	v_y (m/s)	v (m/s)
0.467	7.873	-4.364	9.002
0.500	8.237	-4.961	9.616
0.533	8.064	-4.718	9.342
0.567	7.133	-3.668	8.021
0.600	7.090	-1.803	7.316
0.633	7.231	-0.969	7.296
0.667	7.185	-0.819	7.231
0.700	6.838	-0.760	6.880
0.733	5.685	-1.030	5.777
0.767	4.174	-0.882	4.266
0.800	3.173	-0.249	3.183
0.833			

Figure 2.1: Using Tracker to track athlete's movement in 2-D between frames until head impact. In the prospective videos, depicted here, the light post was the calibration object. In the retrospective videos, the athletes' helmet diameter was the calibration object.

Once the pixel-to-centimeter ratio was found, the crash video was imported into Adobe Photoshop. A stationary object, observable across all frames, was selected within each video. This object was often a light post as the endpoints were clearly defined. The length of the calibration object, in pixels, was measured using the Ruler tool. Using the pixel-to-centimeter ratio, the calibration object's length, in centimeters, was calculated. Importing the video into Tracker, the calibration object was assigned the calculated length by selecting its endpoints. This calibrated the video within Tracker.

Similar to the retrospective videos, the center of the athletes' head was then selected frame-by-frame for the duration of the video. On a calibrated video, tracking the head gave the distance traveled by the athlete down the slope. Because the videos were taken perpendicular to the athlete, the movement of the athlete could be simplified to only the x and y directions. Using the high-speed frame rate of 119.97 fps, the velocity of the athletes could also be calculated within Tracker.

Since these videos were shot at a higher frame rate than the retrospective, the velocities 20 frames before head impact were analyzed. Twenty frames at 119.97 fps correspond to the same time frame as five frames at 29.99 fps. The resultant velocity was found from the x velocity, tangential to athlete’s movement, and y-velocity, normal to movement. The tangential, perpendicular, and resultant velocities from each of the 20 frames before head impact were exported from Tracker and averaged to find the average velocity pre-head impact. This process was repeated separately for each prospective video.

RESULTS

A total of 32 impacts were recorded. Of these, 12 were taken retroactively from previous competition seasons, and 20 were taken prospectively by our research personnel. There were 2 snow boarders recorded and 30 skiers. From these athletes, we observed the locations of head impact and calculated their relative percentage (Table 2.1). The athletes impacted the back of their head 43.75% of the time, a location on the upper occipital region directly on the midsagittal plane. 18.75% of the impacts were rear boss location which also impacted the occipital region, but to the side of the midsagittal plane. 25% of athletes impacted the side of their head which struck the skull in the parietal region. Finally, 12.5% of athletes impacted the front of their head, in the frontal region just above the helmet rim.

Table 2.1: Percentage of head impact location by number of total athletes.

Total	**Back**	**Rear boss**	**Side**	**Front**
n=32	14	6	8	4
percent	43.75	18.75	25	12.5

From each of the 24 analyzable crash videos, the normal, tangential, and resultant velocities were calculated pre-head impact (Table 2.2). The normal velocity represented the velocity the athlete traveled downwards, perpendicular to the slope, in the y-direction. The tangential velocity represented the velocity the athlete went along the slope in the x-direction. The resultant velocity was calculated from the x and y velocities by their square root.

The mean resultant velocity was found to be 5.94 m/s with a standard deviation of 1.67 m/s. The highest resultant velocity was 9.30 m/s corresponding to a rear boss impact. The lowest resultant velocity was 2.74 m/s associated with a side impact. The median resultant velocity was 5.5 m/s, and the 90th percentile was 8.5 m/s.

The mean tangential velocity was 5.34 ±1.69 m/s. The highest tangential velocity, 9.26 m/s, was associated with a rear boss impact, whereas the lowest tangential velocity was 2.51 m/s for a side head impact. The median tangential velocity was 4.7 m/s, and the 90th percentile was 7.4 m/s.

The mean normal velocity was 2.12 ±1.24 m/s. The highest normal velocity was 5.18 m/s, which corresponded to a back of head impact. The lowest normal velocity, 0.32 m/s, was associated with a rear boss impact. The median normal velocity was 2.0 m/s, and the 90th percentile was 3.8 m/s.

Table 2.2: Summary of velocities and calibration method used with each video various source.

Location	Calibration method	Tangential Velocity (m/s)	Normal Velocity (m/s)	Resultant Velocity (m/s)
Deer Valley	Checkerboard	6.70	3.90	7.96
Deer Valley	Checkerboard	9.26	0.32	9.30
Deer Valley	Checkerboard	5.41	0.75	5.47
Deer Valley	Checkerboard	3.59	0.42	3.68
Deer Valley	Checkerboard	4.26	1.85	4.65
New York	Checkerboard	4.06	1.75	4.50
New York	Checkerboard	3.76	2.11	4.34
New York	Checkerboard	3.50	2.96	4.61
New York	Checkerboard	4.59	3.01	5.50
New York	Checkerboard	4.80	1.68	5.11
New York	Checkerboard	4.40	2.78	5.23
New York	Checkerboard	2.51	0.87	2.74
Retrospective	Helmet diameter	4.52	2.16	5.11
Retrospective	Helmet diameter	6.24	0.86	6.37
Retrospective	Helmet diameter	4.06	1.68	4.44
Retrospective	Helmet diameter	3.67	5.18	6.59
Retrospective	Helmet diameter	4.43	0.91	4.56
Retrospective	Helmet diameter	8.40	1.18	8.61
Retrospective	Helmet diameter	7.28	4.31	8.53
Retrospective	Helmet diameter	7.41	3.64	8.33
Retrospective	Helmet diameter	6.99	2.59	7.47
Retrospective	Helmet diameter	6.63	1.37	6.82
Retrospective	Helmet diameter	6.41	2.16	6.77
Retrospective	Helmet diameter	5.30	2.50	5.87

The average normal, tangential, and resultant velocities per head impact location were also calculated to determine which impact location was more likely to result in head injury (Table 2.3). Rear boss had the highest resultant velocity and tangential velocity. However, back of the head impacts produced the highest normal velocity component.

Table 2.3: Average velocities by impact location.

Impact Location	Average Resultant Velocity (m/s)	Average Tangential Velocity (m/s)	Average Normal Velocity (m/s)
Rear Boss	8.23	8.03	1.22
Side	4.97	4.63	1.61
Front	4.73	4.45	1.30
Back	6.08	5.22	2.75

DISCUSSION

The events that were captured included both snowboarders and skiers. Unlike moguls or slalom which are skiing specific, aerialists, freestyle, and big air event types have an equal number of snowboarding and skiing participants. The number of falls between snowboarders and skiers was comparable, however, most of the snowboarding falls captured on video did not have head impact. Our observations were that snowboarders were more likely to catch themselves with their upper body.

The mechanism by which the athletes struck their heads was not distributed evenly across impact locations. The location that was hit most often was back of the head, at 43.75%. This was often due to a scenario called the “backslap” where the athlete over-rotated off a jump and pitched backwards, directly hitting the back of their head. Athletes impacted the rear boss location 18.75%

of the time. Rear boss had a very different crash mechanism than backslaps. During landing, the athletes often slid out sideways, first contacting the ground with their hip or shoulder before head impact. One in four athletes impacted the side of their head. This fall was similar to rear boss, the athletes "caught an edge" and slid out sideways after landing on the slope. They often braced their fall with a hand, leg, or shoulder before hitting the side of their skull. Only 12.5% of athletes impacted the front of their head. This rarity of this occurring was due to the mechanism of head impact. Upon landing, the athlete would pitch forwards down the slope or "somersault" which opposed their backward momentum.

All of the head impacts had a much higher tangential velocity than normal velocity (Figure 2.2). This indicates that snowsport athletes have a greater forward force upon head impact than downward force. Since the normal velocity component was so low, many of the head impacts captured on video were low energy impacts.

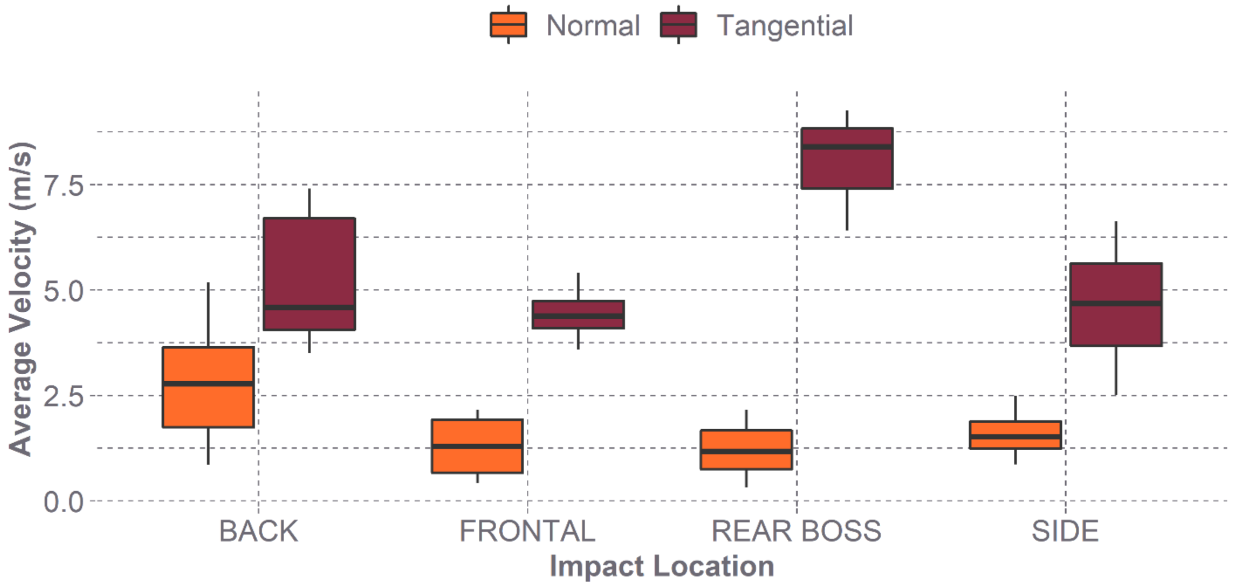


Figure 2.2: Average normal and tangential velocities by head impact location. Higher normal velocities result in more severe head impacts.

The impact location with the highest normal component was the back of the head. This is intuitive as backslaps impact the head without another part of the body absorbing the brunt of the force first. The impact location with the highest tangential velocity was rear boss. This also makes sense as the mechanism of injury for rear boss resulted from sliding along the slope, often hitting other body parts before ultimately impacting the head. This slows down the velocity before head impact substantially due to the friction from the shoulder or leg.

Rear boss impacts produced the highest resultant velocity (8.23 m/s). This was due to the fact that it had a very high tangential component, while its normal velocity was low. In contrast, back impacts had a relatively high resultant velocity (6.08 m/s), but due to a high normal component. Therefore, the likelihood of brain injury for rear boss is lower than the risk of injury from back head impacts because it had a much lower normal velocity.

The method used in this study to find velocities from video had several sources of inherent error. The calibration method had a significant source of potential error as this was a large contributor to the velocity values. For the prospective videos, a calibration board was used to find the pixel space within each video. However, this was left up to the observer's discretion to decide which pixel exactly corresponded to a point on the calibration board. For the retrospective component, the videos were calibrated using the diameter of the helmeted in the frame right before head impact. However, helmets are not perfect circles, but ovular. Therefore, if the head was turned the long direction, we estimated 75% of the head diameter to be the calibration length. Another source of error in the retrospective videos could have occurred during the stabilization process. Although professional computer software was used for this task, there was still slight background movement between frames that could not be eliminated. Both methods used video tracking to obtain the final velocities where the center of the helmeted head was selected within each video frame. There was inherent error with this process as the center of the head was subjectively determined by the observer. One limitation which this approach is that it simplified the 3-D movement of the athletes to x and y directions only, giving the tangential and normal components of the pre-impact velocities. Future work would include finding the velocities in all 3-dimensions.

Additionally, the small sample size in this study could have produced bias in the results. Originally, the aim had been to video more prospective events, however, due to the effects of COVID-19, all on-slope data collection had to be terminated early. The data collected was mostly on aerialists which would have biased the distribution of head impact locations that were found. Also, all of the video collected was on Olympic-level snowsport athletes, which likely travel at higher speeds and more aggressively than a beginner snowboarder or skier. Therefore, the results of the head impact locations and velocities cannot be generalized to whole the snowsport population. Future work would include taking video of more snowsport head impacts over a broader range of snowboarding and skiing events to obtain a larger range of velocities pre-head impact and better understand the common head impact locations within the snowsport population.

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CHAPTER 3

Development of a Test Method to Compare Snowsport Helmet Performance

ABSTRACT

To ensure safety across helmet models, the U.S. requires all snow helmets to pass two testing standards: ASTM 2040 and CE EN 1077. While these standards may effectively assess the helmet's ability to prevent catastrophic injury for set impact conditions, they fail to characterize real-world scenarios. There has been limited research on real-world snowsport head impacts with only one study that correlates the head impact into a laboratory setting. With the prevalence of head injury in snowsports, testing snowsport helmets in a realistic manner is essential to preventing against brain injury. Therefore, the purpose of this study is to develop a test methodology representative of snowsport head impacts that can highlight differences in the relative ability of helmets to reduce concussion risk. To complete this objective, data collected from video of real-world head impacts were used to create representative impact conditions in a laboratory setting. A test protocol was developed to evaluate commercially available helmets. Helmet performance was quantified by the summation of tests for the analysis of risk (STAR) equation. We evaluated 6 helmet models using this approach. Overall, the consistency in this laboratory testing method was good, with small variance between paired trials. The kinematics from each drop test were used to calculate the injury risk for each helmet model. The average injury risk was 51.1 ± 29.7% with an overall reduction in risk of 53.7% from best helmet to worst. The impact location with the greatest risk was front, and the least was side. Testing at a higher normal velocity increased the risk of injury by 40.5%. The risk was lower with the tangential velocity impacts but had a larger variance. The average injury risk values per helmet model determined that helmet's comprehensive STAR value, which ranges from 0.00 to 6.00, where 0 indicates the helmet performed well. The STAR

values from this study ranged from 2.22 to 4.12, with an average of 3.07 ± 0.64. Future work will include evaluating all commercially available helmets on the market. The results of each helmet model will be released to the public to inform prospective consumers of relative performance. As a result, the testing system will lead to design interventions that ultimately reduce the risk of injury, revealing how this basic science approach will have a significant real-world impact.

INTRODUCTION

Historically, the use of helmets in snowsport activities has been low, with only 12% of skiers and snowboarders wearing a helmet in 2001.[1] However, the prevalence of helmets on the slope had increased to approximately 75% by 2019.[2, 3] This initial low compliance can partially be attributed to the controversy around the effectiveness of helmets. With some studies showing that snow helmets had no significant effect in protecting against brain injury and others believing that helmets actually contributed to injuries by either increasing spine injury or promoting riskier behavior.[4, 5] Although these assumptions have been proven false through continued research,[3, 6-8] there has been variability in the statistics. Helmets have been shown to protect against injuries from 20% to as great as 60% of the time.[6, 9-12]

To ensure consistency and safety across helmet models, the U.S. required competition helmets to adhere to the International Ski Federation (FIS) requirements before they are allowed to be sold commercially. The FIS enforces all snow helmets to pass the American ASTM 2040 and European CE EN 1077 Class B testing standards. However, in 2013, FIS increased the specifications for competition helmets used for the alpine events: giant slalom, super giant slalom, and downhill. These must be certified by both ASTM 2040 and EN 1077 Class A standards, plus withstand an impact of 6.8 m/s onto flat anvil.[13]

CE EN 1077 has two tests to evaluate snow helmets. Class B testing involves dropping a helmeted headform onto a flat anvil at 5.52 m/s. The peak acceleration must remain under 250 g. The helmets also undergo a penetration test where they must resist a 3kg striker dropped at 0.375 m onto the helmet. For Class A, the helmets must pass the Class B drop test, in addition to a more rigorous penetration test. The striker is dropped at 0.75 m onto the helmet. The tests are performed at ambient room temperatures, -25C, and artificial aging.

ASTM 2040 is another test standard used for snow helmets. This requires a helmeted 5kg headform to be dropped at a velocity of 6.2 m/s onto flat anvil. The peak acceleration of the headform must remain under 300 g. The test also includes dropping the helmet at a height of 1.25 m onto a hemispherical anvil, and from 1 m onto an edge-shaped anvil. These tests are performed at ambient temperature, -25 degrees C, 35 degrees C, and immersed in water.

One issue with these standards is that they are pass/fail, which gives users no indication of which helmets reduce risk better than others. Also, although these tests may provide sufficient methods to test the protective capabilities of a helmet under specific impact conditions, they don't consider rotational kinematics, and the potential high tangential velocities in real-world scenarios. These testing standards only evaluate helmets ability to protect against normal velocity impact, when real-world crashes most often involved both tangential and normal velocity components. Normal force is perpendicular to the ground which causes the linear impact on the head. Tangential force is the sideways force, along the ground, which causes rotation of the head. Decades of research on concussion have proven that a combination of both rotational and linear kinematics are most indicative of brain injury.[14-19] Therefore, including tangential impact velocities and considering rotational head kinematics in helmet testing can provide additional insight on helmet performance.

There have been limited laboratory reconstructions of real-world crash events in snowsports.[20-24] One study analyzed 9 head impacts to determine if the pre-impact velocities were higher than FIS helmet specifications.[21, 22] Although they found the average speeds skiers and snowboarders go pre-head impact are higher than the FIS helmet test standard of 6.8 m/s, but did not replicate these real-world data to a laboratory test. Another study investigated the potential for neck injury in snowsport aerialists with and without helmets.[23] Through laboratory drop testing, they found helmets reduced head acceleration by 32-48% in hard snow but had little effect on soft snow or on neck loading. Another experiment studied the effect of repeated slow impacts, such as ski gates, would have on snowsport helmets.[24] They found that helmets with expanded polystyrene (EPS) cores fared worse than and expanded polypropylene (EPP) helmets, however, both were better than unhelmeted headforms. However, this study again lacked any real-world data informing their testing. Only one study, replicating a single head impact, took video of a real world impact and using model-based image-matching[25] with video analysis obtained real-world kinematics which were then translated into laboratory testing.[20] However, their lengthy analysis processes yielded only one datapoint. None of these studies have been used to evaluate a plethora of commercially available helmets. The purpose of this study is to develop a test methodology representative of snowsport head impacts in real-world that can highlight differences in the relative ability of helmets to reduce concussion risk.

METHODS

To determine representative impact conditions, data from real-world head impacts were used. These data, collected from video of real-world head impacts, included the head kinematics before impact, the impact location on the helmet, the angle of the impact slope, as well as its surface composition. By creating representative impact conditions from real-world data, we developed a laboratory system that can replicate impact events in snowsports. Using this laboratory test to generalize head impacts in snowsports, we created a test protocol that was used to evaluate commercially available helmets.

A drop tower was used to evaluate the helmet models at the different impact configurations determined from previous video data collected from real-world head impacts. The drop tower is comprised of a support ring which holds the helmeted headform in place. This ring contained 5 independently adjustable rods that allowed for each impact location to be set. To set the headform into the correct position, a dual-axis inclinometer was used. A lever arm held the headform onto the ring during the drop. This lever released just before impact to allow the head to move upon impact. Three linear accelerometers (Endevco 7264B-2000, Meggitt Sensing Systems, Irvine, CA), as well as a triaxial angular rate sensor (ARS3 PRO-18K, DTS, Seal Beach, CA) were mounted at the headform's center of gravity. Upon impacting an oblique anvil, these measured the head kinematics in all six degrees of freedom.

The tests were conducted using a medium National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform which was chosen because of its human-like shape and response upon impact. Its surface has a lower friction compared to other headforms also contributing to its biofidelic response.[26, 27] A neck was not used due to added variance between trials and its non-human-like response under vertical impact conditions.[28]

In snowsports, the crash events occur over an angled surface, therefore, the helmeted headform was dropped onto an adjustable oblique anvil, as opposed to a flat anvil in the standards testing. The degree to which the anvil was angled was determined by the normal and tangential velocities found from our video analysis of real-world impacts. Because lower velocity impacts do not represent injurious data, these were not considered in our laboratory testing. The 90th percentile of helmeted impacts from video consisted of 7.4 m/s tangential velocity and 3.8 m/s normal velocity. The EN 1077 Class B standards require the helmet to withstand a normal velocity of 5.52 m/s. Given that normal velocity creates a greater force between the helmet and the impact surface so more indicative of head injury, we tested at normal velocities of 3.8 m/s and 5.5 m/s.

The helmet's ability to manage normal and tangential impact forces was assessed by varying these component velocities while keeping the resultant velocity the same between trials at 6.7 m/s (Table 3.1). This was accomplished by changing the angle of the anvil. For the higher normal velocity condition of 5.5 m/s, we used an angle of 35 degrees which resulted in a tangential velocity of 3.8 m/s. For higher tangential velocity condition of 5.5 m/s, we used a 55-degree anvil which gave normal velocities of 3.8 m/s. To achieve these angles, the adjustable anvil was positioned with a digital angle gauge (Wixey, Model NO.WR300 Type 2). To ensure consistency between tests, the resultant velocity was measured each drop with a light gate (Velocity Timer Model 1204, KME Company, Troy, MI). The impact velocities were within ± 0.55 m/s of the target value.

Table 3.1: The two different velocity conditions tested for each helmet model. The velocity components were varied by adjusting the anvil angle.

Anvil Angle	**35°**	**55°**
Normal Velocity (m/s)	5.5	3.8
Tangential Velocity (m/s)	3.8	5.5
Resultant Velocity (m/s)	6.7	6.7

The inconsistency in snow conditions make them difficult to simulate in a laboratory setting. Snow and ice have very different frictional properties and degree of hardness that change due to fluctuations in weather. These can significantly affect how helmets react upon impact. Additionally, any compliancy in the test system can mask helmet performance. So, to keep consistency between trials, we chose to use one rigid impact surface with a friction coefficient similar to hard snow. As helmets are designed of hard plastic, we used Polytetrafluoroethylene (PTFE), a common hard plastic, for comparison. The static coefficient of friction for PTFE on snow is 0.05, which is within the range of PTFE on bare steel, 0.05-0.2.[29] Therefore, we chose to use bare steel as our ice simulating surface as it will remain consistent between tests and help isolate helmet performance.

The helmets were positioned to impact the bare steel, oblique anvil at 3 specific locations (Figure 3.1). These were based off the common mechanisms of head impact observed from skiers and snowboarders from our video analysis and literature.[30] The first location (rear boss) simulated a backwards fall, or “backslap” and encompassed both the back of the head impacts and the rear boss impacts that were identified in video analysis. This location was positioned on the upper occipital region, slightly right of the midsagittal plane to avoid interference with the goggle attachment piece that is present in most snowsport helmets. The second location (side) simulated a sideways fall or “catching an edge” and was positioned to impact the parietal region. The third location (front) simulated the athlete pitching forward after landing or “somersaulting.” This impacted the helmet in the frontal region just above the helmet's rim.

Figure 3.1: Snowsports helmets were tested at three impact locations, rear boss (left), side (middle), and front (right). Helmets were dropped once at each of these positions onto an oblique anvil of 35° and 55°.

In this study, 6 different helmet models were tested, four from each model for a total of 24 helmets. The helmet models were chosen to encompass a range of brands, rotational technology, and cost. These included Smith, Giro, Sweet Protection, Anon, Atomic, and POC (Table 3.2). All helmet models were certified under ASTM 2040 and CE EN 1077 Class B testing standards. The helmets ranged in price from $150 to $475. The inclusion of Multi-directional Impact Protection System (MIPS) was present in 2 of the helmet models. MIPS is a slip-plane layer between the head and helmet intended to reduce rotational head kinematics resulting from impact. Two models included brand-specific anti-rotational technology, Shearing Pad Inside (SPIN) and Atomic Multi-directional Impact Deflector (AMID). Any internal helmet features such as retention systems and anti-rotational technology were re-secured between tests when necessary. Goggles and other extraneous attachments were removed before testing.

Table 3.2: Helmet models used for STAR evaluation. The price range varied according to model and the inclusion of MIPS.

Helmet Model	Anti-rotational Technology	Price ($)
Smith Maze	MIPS	150
Giro Orbit	MIPS	475
Sweet Protection Switcher	No	240
Anon Echo	No	160
Atomic Four	AMID	150
POC Obex	SPIN	200

A total of 12 impacts per helmet model were performed with the 6 different helmet models at the 3 locations and 2 anvil angles (Figure 3.2). Two identical helmets were dropped once at each impact location onto the shallower, 35° anvil, resulting in the high normal velocity condition (N). Their identical matched pairs were dropped once at each location onto the steeper, 55° anvil, resulting in the high tangential velocity condition (T).

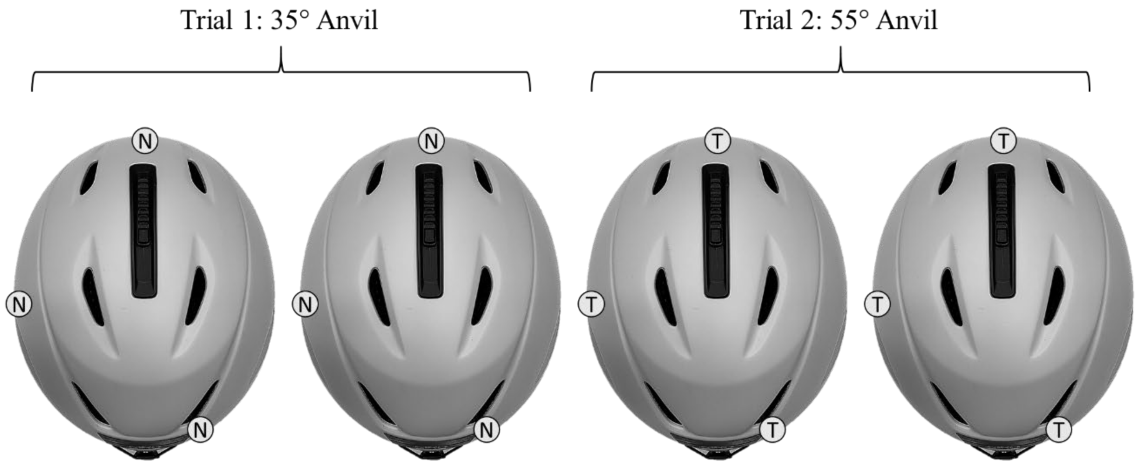

Figure 3.2: Test matrix for one helmet model. Two helmets were dropped at 35° anvil, with a higher normal velocity (N). Their matched pairs were dropped at the 55° anvil, with a higher tangential velocity (T).

Linear acceleration and rotational velocity data were collected at 20 kHz for each test. The kinematic data were filtered 4-pole phaseless Butterworth filters of channel frequency class 1000 for linear acceleration and 175 for rotational velocity. Resultant peak linear acceleration (PLA) and peak rotational velocity (PRV) were calculated for each test.

Helmet performance was characterized by adapting the STAR evaluation system to the snowsport impact environment.[31] First, the injury risk for each impact condition was calculated using a concussion injury risk function (Equation 1).[31] Using PLA, a, and PRV, ω, this function evaluates the risk of injury from impact tests. PRV was the chosen rotational metric, rather than PRA, because it has less measurement variability and accounts for duration of loading. It has also been shown to correlate better to the concussive-causing strain developed in the brain.[33, 34]

$$R(a,\omega) = \frac{1}{1+e^{-(-10.2+0.0433*a+0.19686*\omega-0.0002075*a\omega)}} \qquad \text{Eqn. (1)}$$

The PLA and PRV values from each impact test were averaged across the two identical tests within each trial, to obtain average PLA and average PRV per impact condition. An average injury risk per impact condition was then calculated from these average kinematics. Using the snowsportSTAR equation (Equation 2), the average injury risks per impact condition were used to compute a single STAR value for each helmet model. The STAR equation condenses a range of tests into a single metric that evaluates helmet performance. The snowsport STAR equation is similar to the previously-published bicycle STAR equation with slight modifications.[31] The exposure term, E, weights each impact configuration based on its frequency in the real-world which includes a location, L, and velocity, V.

$$SnowsportSTAR = \sum_{L=1}^{6} \sum_{V=1}^{2} E(L, V) * R(a, \omega) \qquad \text{Eqn. (2)}$$

There are not enough published data to make broad generalizations on which impact locations and velocities are most common across all snowsport types and events. Therefore, all three impact locations were weighted equally with the exposure term equal to 1 for every impact test. With an exposure of 1, the risk values for each helmet were summed to determine the final STAR values.

The data were analyzed through mixed effects ANOVA models with the factors impact location, and velocity, and the random effect of helmet model. This was done separately on PLA, PRV, and risk to understand how each was influenced by these factors (RStudio, V 1.4.1106, Inc., Boston, MA). A least square means pairwise comparison with a Tukey adjustment (at 95% confidence level) was also completed for further insight into the effect interactions.

RESULTS

The 6 helmet models tested produced a wide range of kinematics results across impact scenarios (Table 3.3). Overall, the consistency in this laboratory testing method was good for PRV, with a variance of 2.4 rad/s between identical helmet impact scenarios. However, the variance within each trial for PLA was much higher, 39.4 g. The impact durations were similar between the high normal conditions and high tangential conditions but differed on average by 1.8 ms (8.70 ± 0.6 ms for the normal condition versus 10.5 ± 1 ms for the tangential condition).

Table 3.3: Average PLA, PRV, and risk summarized by each impact condition.

Impact Location	High Velocity Component	Average PLA (g)	Average PRV (rad/s)	Average risk (%)
Rear Boss	Normal	196.4 ± 16.3	16.7 ± 3.7	0.7 ± 0.2
Rear Boss	Tangential	135.8 ± 9.9	19.2 ± 4.8	0.3 ± 0.2
Side	Normal	208.7 ± 14.8	14.6 ± 3.5	0.7 ± 0.1
Side	Tangential	141.4 ± 13.9	12.9 ± 4.0	0.1 ± 0.1
Front	Normal	200.3 ± 21.1	19.3 ± 3.8	0.8 ± 0.2
Front	Tangential	128.9 ± 21.3	22.1 ± 10.6	0.5 ± 0.3

The average PLA across all impact scenarios was 168.6 ± 37.2 g. PLA was found to be influenced by velocity ($p < 0.0001$), while location had only a small affect ($p= 0.066$). Under high normal velocity conditions, the average PLA was 201.8 ± 17.6 g, while under high tangential velocity conditions, the average PLA was 135.5 ± 16.0 g. The impact location with the highest PLA was side in both velocity conditions (Figure 3.3).

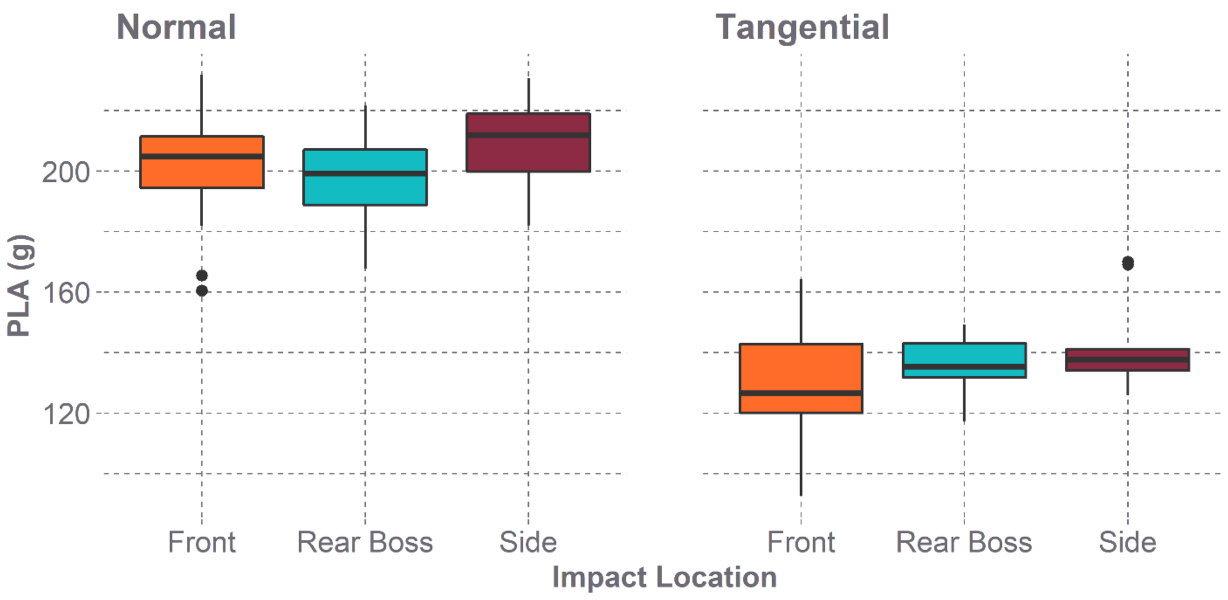

Figure 3.3: Peak linear accelerations across impact locations for each velocity condition.

The average PRV across all impact scenarios was 17.5 ± 6.2 rad/s. PRV was influenced by location only ($p < 0.0001$). Under high normal velocity conditions, PRV averaged 16.8 ± 4.0 rad/s, not significantly different than the average PRV under high tangential velocity conditions, 18.1 ± 7.8 rad/s. Across both velocity conditions, the impact location with the highest PRV was front and the lowest was side (Figure 3.4).

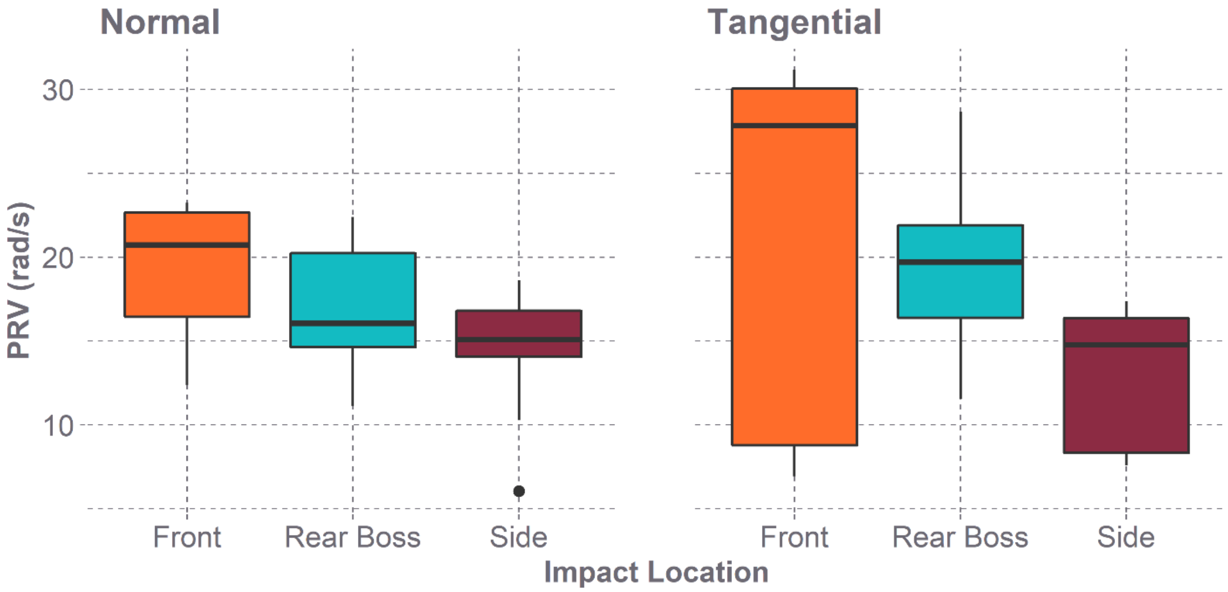

Figure 3.4: Peak rotational velocities across impact locations for each velocity condition.

The average injury risk across all helmet models was 51.1 ± 29.7%. The lowest risk, 1.0%, was associated with the Smith Maze MIPS helmet at the side impact location under a tangential condition. The highest risk, 91.7%, was associated with the Sweet Protection Switcher helmet at the front impact location under a normal velocity condition. The impact location with the greatest risk on average was front, while the lowest was side (Figure 3.5).

The effect of velocity on risk was considerable ($p < 0.0001$), while location had a small affect ($p = 0.070$). The average risk associated with the normal condition was 72.8 ± 17.6%, while the average risk for the tangential condition was 29.5 ± 24.7%, therefore, testing at a higher normal velocity increased the risk of injury by 40.5%. The risk was lower in the tangential condition but had a larger variance (Figure 3.5).

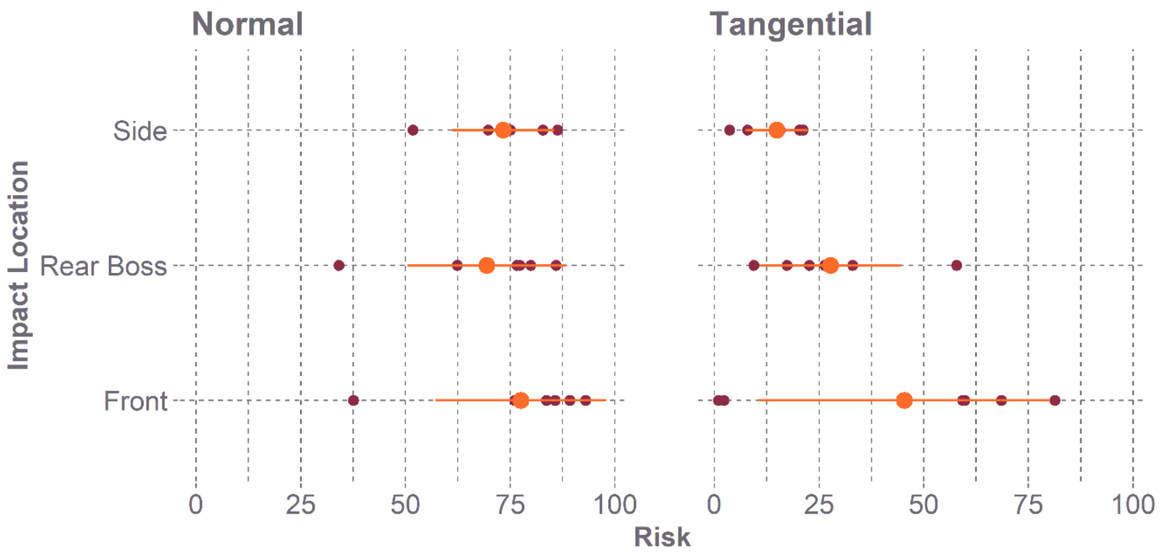

Figure 3.5: The distribution of risk across head impact location and velocity condition with the mean value and standard error bars overlayed.

The average injury risk values per helmet model added together determined the helmet's comprehensive STAR value (Table 3.4). STAR values range from 0.00 to 6.00, where a STAR value of 6 indicates the helmet did poorly in protecting against PLA and PRV, and a STAR value of 0 shows the helmet performed outstandingly. The average STAR rating was 3.07 ± 0.64. The helmet model that performed best was Sweet Protection Switcher, while the helmet that performed worst was Smith Maze MIPS.

Table 3.4: STAR value and risk calculated for each helmet model.

Helmet Model	**Average Risk (%)**	**STAR Value**
Smith Maze MIPS	36.9 ± 32.8	2.22
Giro Orbit MIPS	41.7 ± 37.6	2.50
Atomic Four AMID	46.9 ± 31.1	2.82
Anon Echo	56.0 ± 29.6	3.36
POC Obex SPIN	58.0 ± 26.1	3.48
Sweet Protection Switcher	68.7 ± 27.0	4.12

The effect of velocity condition and impact location to the STAR value of each helmet model could also be assessed with this laboratory method (Figure 3.6). Impact locations gave relatively even contributions to the STAR values. However, velocity conditions had a large effect on the STAR value. As expected, the normal condition contributed by a much greater extent to a helmet's STAR score than the tangential condition.

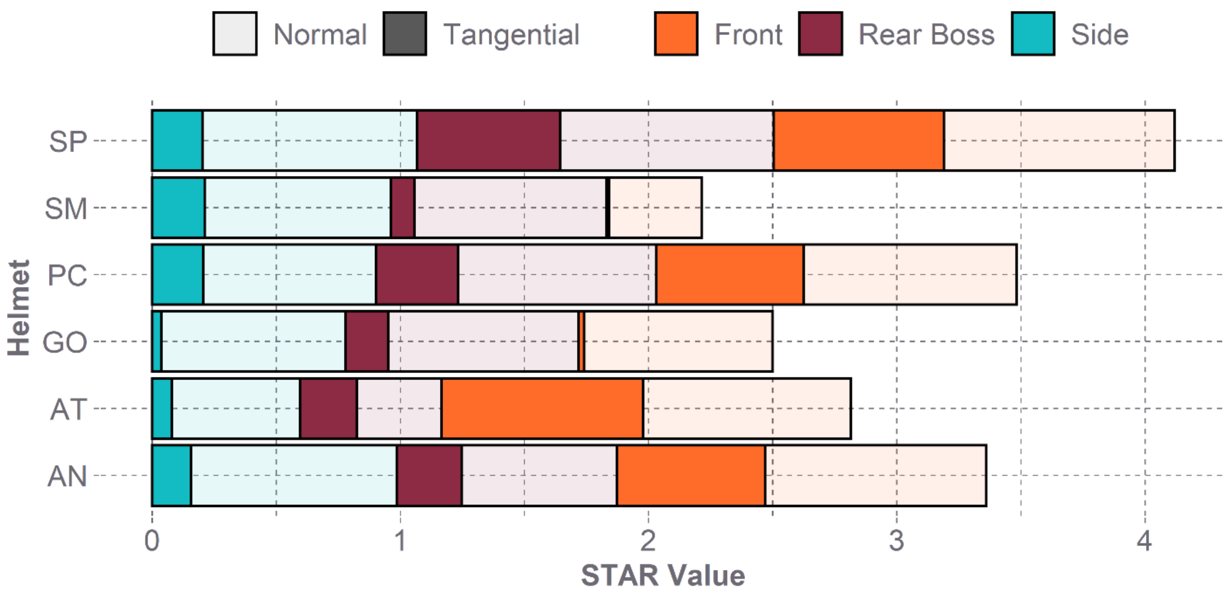

Figure 3.6: Helmet model performance based on STAR value. Each helmet's STAR value is broken down by impact location and velocity condition to show the individual contribution of each to the overall score.

DISCUSSION

This study describes the development of a laboratory method to evaluate snowsport helmets in a manner more consistent with real-world head impacts than standards testing. The method was applied to 6 exemplar snowsport helmets to demonstrate its ability to highlight differences in overall performance. The helmets were tested at 3 different impact locations (back, side, and front) based on those commonly seen in real-world scenarios. The helmets were tested on an oblique anvil at the resultant velocity of 6.7 m/s, but with varying anvil angles. One impact condition, the anvil angle was 35°, producing a higher normal velocity component, while the other impact condition tested at 55° anvil, producing a higher tangential velocity component.

Although all drop tests were run at 6.7 m/s, varying anvil of the angle creates two distinct impact conditions to evaluate helmet performance. Velocity had a significant effect on PLA. As expected, linear acceleration was found to be greater under the high normal velocity condition by 66.4 g on average. This was because normal velocity caused a greater linear force between the helmet and the anvil. However, velocity did not have a significant impact on PRV. Under the normal condition, PRV was on average 1.32 rad/s lower than observed in the tangential condition. Risk increased significantly under normal conditions due to the fact that the higher normal velocity caused a greater force between the helmet and the impact surface.

Location had only a small effect on PLA, which makes sense as the linear acceleration would not depend on which part of the helmet was struck as much as how great of a normal velocity the helmet experienced. In contrast, location heavily influenced PRV. This follows what we expected since striking different parts of a non-spherical helmet would cause great differences in the rotation. On average, the location with the greatest risk was front impacts and the least was side with a difference of 17.3%.

Injury risk varies from 0% to 100%, where a value of 0% shows that the helmet completely protected against the linear accelerations and rotational velocities from the head impact, and a risk of 100% demonstrates that the helmet did nothing. A higher injury risk indicates that brain injury would likely result if the laboratory head impact scenario occurred in real world. The average injury risk was 51.1%. the risk values were not all 100% or 0%, this indicates the test method can assess helmet performance over a broad spectrum of quality. An average injury risk of around 50%

demonstrates that the impact conditions are testing a meaningful range of kinematics. The wide range of results allows manufacturers the ability to improve helmet performance based on this methodology to ultimately minimize injury risk.

The broad collection of kinematic results were summarized with STAR values. The STAR value is an estimation of the number of concussive injuries that might happen within the number of impacts that were replicated in the laboratory. The STAR values in this study ranged from 2.22 to 4.12, with an average of 3.07 ± 0.64. However, if a greater number of helmets were tested, this would likely result in a larger range of STAR values. The helmet that performed worst was Sweet Protection Switcher, produced from an average PLA of 177.2 ± 37.6 g and an average PRV of 21.9 ± 4.8 g. The best performing helmet was Smith Maze with an average PLA of 166.2 ± 36.1 g and an average PRV of 12.0 ± 3.6 rad/s. There was a 53.7% reduction in risk from the best helmet to the worst.

Only 6 models were evaluated for demonstrative purposes, so we can't describe trends based on anti-rotational technology and price. However, we can note that the helmet model that performed worst was a $240 helmet with no anti-rotational technology, while the helmet that performed best was the cheapest helmet, $150, and included MIPS. With more testing, relationships between cost and helmet technology should help consumers identify the best head protection for their needs.

There are several limitations associated with this study. Although real-world data were used to inform our testing, there is not enough published literature to determine the exposure associated with each impact configuration. Therefore, for this study, we calculated the STAR values with an exposure term of 1 for every impact location and velocity condition. This assumes each impact is equally likely to occur and allowed us to observe relative differences in performance across helmet models. However, to make this test method more similar to real-world head impacts, future work would include obtaining more data on the locations and speeds snowsport athletes experience upon head impact.

This study tested at 6 head impact configurations: 3 head impact locations at 2 velocity conditions. In real-world, head impacts can occur at any location on the head. By limiting the impact locations to only 3, this study did not assess the full protection capabilities of each helmet. There likely exists locations on helmets not evaluated that vary in their level of protection. Additionally, the velocity conditions used in this study were not completely representative of the velocities seen in real-world. Most of the head impacts taken from video had very high tangential velocity components with very low normal velocity components. Due to the high tangential velocity contribution, the resultant velocities were often greater than could be simulated with our laboratory system. By varying the tangential and normal velocities between high and low, we could test at a more reasonable resultant velocity, while still evaluating how a relatively high tangential velocity influences helmet performance.

The impact surface was also a limitation. In real-world, head impacts occur over snow or ice, however, these could not be replicated in the laboratory. Bare steel was used as the impact surface due to its similar coefficient of friction but could not exactly mimic the surface composition of snow or ice.

A neck was not incorporated as a part of this study. Although previous testing has shown it to have a biofidelic response under some impact scenarios, under oblique impact tests, significant axial load is placed on the neck which causes the neck to behave in a manner not consistent with a human neck response.[27, 28] The instrumentation used to collect the kinematic data has limitations regarding rotational velocity.[32]

Finally, the dataset was small, consisting of only 6 helmet models. A sufficient number of helmets were tested to ascertain if the developed protocol could identify differences between snowsport helmets. Future work would include testing a greater number of helmets to make more accurate predictions on how design differences, varying velocity components, and different impact locations can influence snowsport helmet performance.

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CHAPTER 4

Closing Remarks

SUMMARY OF RESEARCH

The purpose of this study was to understand the head impact conditions in a snowsport environment and use the data to inform laboratory testing to evaluate current snow helmet design.

First, we investigated the effects of friction in snow helmet testing. We tested 10 different helmet models, with 5 including MIPS under low and high friction conditions. Each of the helmets were dropped at two locations, rear boss and side. Resultant peak linear acceleration (PLA) and peak rotational velocity (PRV) were calculated for each test. We found the higher friction condition corresponded to higher linear accelerations but lower rotational velocities. MIPS did not influence PLA but affected PRV to varying degrees depending on impact condition.

Secondly, we studied the head impacts in a snowsport environment to understand the common impact locations and the associated kinematics pre-head impact. Working with the men's and women's U.S. Ski and Snowboard Team, we implemented video analysis techniques to quantify the boundary conditions of head impacts sustained by participants. We found rear boss impacts produced the highest resultant velocity (8.23 m/s), followed by back impacts (6.08 m/s). Side impacts (4.97 m/s) and front impact (4.73 m/s) had similar resultant velocities. All of the head impacts had a much higher tangential velocity than normal velocity. The impact location with the highest normal component was the back of the head which was also the location that was hit most often.

Lastly, we developed a test protocol that could emphasize differences in the relative protective capability of helmets using representative impact conditions from real-world scenarios. Six helmet models were evaluated under 2 velocity conditions and 3 impact locations, and their performance quantified by their STAR values. With this test method, the average injury risk was approximately 50%. The impact location with the greatest risk was front, while the least was side, and testing with a higher normal velocity condition increased the risk of injury. The STAR values from this study ranged from 2.22 to 4.12, with an overall reduction in risk of 53.7% from best helmet to worst. The results from this research provide prospective consumers with unbiased impact data to make informed helmet purchases, while concurrently allowing for helmet design interventions to reduce the risk of injury.