applied sciences

MDPI

Article

Radial and Oblique Impact Testing of Alpine Helmets onto Snow Surfaces

Declan A. Patton [1,2,3,4,*], Reza Mohammadi [5], Peter Halldin [5], Svein Kleiven [5] and Andrew S. McIntosh [1,6]

[1] Australian Collaboration for Research into the Injury in Sport and Its Prevention (ACRISP), Federation University Australia, Ballarat, VIC 3350, Australia
[2] Oslo Sports Trauma Research Center (OSTRC), Norwegian School of Sport Sciences, 0863 Oslo, Norway
[3] Sport Injury Prevention Research Center (SIPRC), Faculty of Kinesiology, University of Calgary, Calgary, AB T2N 1N4, Canada
[4] Center for Injury Research and Prevention, Children's Hospital of Philadelphia, Philadelphia, PA 19104, USA
[5] Division of Neuronic Engineering, KTH—Royal Institute of Technology, 11428 Stockholm, Sweden
[6] McIntosh Consultancy & Research, Sydney, NSW 2090, Australia
* Correspondence: declan@unswalumni.com

Abstract: Recent studies have found that alpine helmets reduce the risk of focal injuries associated with radial impacts, which is likely due to current alpine helmet standards requiring helmets to be drop-tested on flat anvils with only linear acceleration pass criteria. There is a need to evaluate the performance of alpine helmets in more realistic impacts. The current study developed a method to assess the performance of alpine helmets for radial and oblique impacts on snow surfaces in a laboratory setting. Snow samples were collected from a groomed area of a ski slope. Radial impacts were performed as drop tests onto a stationary snow sample. Oblique impacts were performed as drop tests onto a snow sample moving horizontally. For radial impacts, snow sample collection time was found to significantly ($p = 0.005$) influence mean peak linear headform acceleration with an increase in ambient temperature softening the snow samples. For oblique tests, the recreational alpine sports helmet with a rotation-damping system (RDS) significantly ($p = 0.002$) reduced mean peak angular acceleration compared to the same helmets with no RDS by approximately 44%. The ski racing helmet also significantly ($p = 0.006$) reduced mean peak angular acceleration compared to the recreational alpine sports helmet with no RDS by approximately 33%, which was attributed to the smooth outer shell of the ski racing helmet. The current study helps to bridge the knowledge gap between real helmet impacts on alpine snow slopes and laboratory helmet impacts on rigid surfaces.

Keywords: alpine sports; head injury; helmets; impact biomechanics; injury prevention; protective equipment; skiing; snowboarding

check for updates

Citation: Patton, D.A.; Mohammadi, R.; Halldin, P.; Kleiven, S.; McIntosh, A.S. Radial and Oblique Impact Testing of Alpine Helmets onto Snow Surfaces. *Appl. Sci.* **2023**, *13*, 3455. https://doi.org/10.3390/app13063455

Academic Editors: Enrique Navarro, Alejandro San Juan Ferrer and Santiago Veiga

Received: 9 January 2023
Revised: 27 February 2023
Accepted: 3 March 2023
Published: 8 March 2023

1. Introduction

Head injuries are common in skiing and snowboarding at both the recreation and elite levels [1–3]. Helmet use by recreational skiers and snowboarders has increased in recent decades [4]. Several earlier studies reported that helmets were associated with a reduction in the risk of head injury in skiing and snowboarding [5–7]. In contrast, Baschera et al. [8] found no significant decrease in severe traumatic brain injury among alpine skiers despite an increase in helmet use. Similarly, Sulheim et al. [9] observed an unexpected reduction in the protective effect of helmets in alpine skiing and snowboarding, which was suggested to be a result of new skiing trends. For paediatric skiers and snowboarders, Milan et al. [10] found that wearing a helmet was significantly associated with intensive care admission; however, injury severity was significantly lower compared to those not wearing a helmet. Bailly et al. [11] found that helmet wearers were less likely to sustain any head injury; however, the effect of helmets on preventing traumatic brain injury was non-significant.

More recently, Porter et al. [12] found helmet use was associated with a significant reduction in skull fracture but a significant increase in intracranial haemorrhage.

Alpine helmet standards require helmets to be drop tested on flat anvils at impact speeds ranging from 4.5 to 6.8 m/s with peak linear headform acceleration remaining below 250 or 300 g [13–17]. Some alpine helmet standards also require helmets to be drop tested on hemispherical and edge anvils [13,16,17], which are intended to represent hazards, such as a rock or tree stump. Currently, no alpine helmet standard includes an oblique impact test with rotational criteria, such as angular acceleration and/or angular velocity. It is unknown how drop tests onto rigid anvils relate to impacts on snow and ice surfaces; however, several studies have investigated head impacts on snow surfaces to bridge the knowledge gap between standards tests and real-world impacts [18–25].

Anthropomorphic test devices (ATDs) have been used to simulate rearward falls onto snow slopes resulting in occipital head impact [18–20], which has been identified as the mechanism of over half of all major head injuries to snowboarders [26–29]. A Hybrid III ATD was accelerated along a cable and released at approximately 8 m/s onto a snow-covered ramp with a gradient of 20°, which was used to replicate a snow slope. The ATD was outfitted with snowboarding attire and equipment, which comprised boots, bindings and a snowboard. For soft snow conditions, the ramp was covered in 300 mm of snow. For icy snow conditions, the soft snow on the ramp was allowed to freeze and covered in an additional 100 mm of soft snow. A small mound of snow was formed on the ramp so that the rear edge of the snowboard caught and resulted in the ATD falling rearwards down the ramp. For soft snow impacts to the occiput, all peak linear headform accelerations remained below 83 g for all soft snow impacts, and no significant differences were found between the helmeted and unhelmeted conditions. In contrast, icy snow impacts to the occiput of the unhelmeted and helmeted headform resulted in mean peak linear accelerations of 391 and 162 g, respectively. Therefore, the presence of the ski helmet was found to significantly reduce peak linear headform accelerations by a factor of over two for icy snow impacts. Dressler et al. [21] investigated the protective potential of a ski helmet for 4 m/s drop tests into 150 mm deep snow samples using a Hybrid III head-neck system attached to a carriage with a total mass of 16 kg to represent the torso. Hard snow samples were prepared by filling the trays with snow and allowing them to freeze overnight, whereas soft snow samples were prepared by allowing a 60 mm layer to freeze overnight and adding 90 mm of soft snow prior to testing. Samples were removed from the freezer and allowed to thaw at room temperature for approximately 2.5 h before testing. For soft snow impacts to the crown, no significant protective effect was observed in the helmeted tests, and all peak linear headform accelerations remained below 42 g for all soft snow impacts, and no significant differences were found between the helmeted and unhelmeted conditions. In contrast, hard snow impacts to the crown of the unhelmeted and helmeted headform resulted in peak linear acceleration ranges of 138–165 g and 79–98 g, respectively; therefore, the presence of the ski helmet was found to significantly reduce peak linear headform accelerations by 32–48%. Dressler et al. [21] stated that the quality and consistency of snow samples were a limitation and suggested that future studies investigate snow hardness at ski resorts. Such drop tests evaluate the effectiveness of alpine helmets for radial impacts, which are associated with a focal head injury, such as a skull fracture [18].

Few studies have investigated alpine helmets in oblique impacts, which comprise a rotational component and are associated with a diffuse head injury, such as intracranial haematoma [22]. Kleiven et al. [23] dropped a helmeted headform from a height of 1.7 m onto a snow slope, from which the acceleration and high-speed video data were used to reconstruct impacts and validate a finite element snow model. In a similar study, Bailly et al. [24,25] obtained the damping properties of hard and soft snow by performing drop tests on ski slopes using a rigid headform from various heights. It was concluded that a relevant impacting surface and more demanding acceleration criteria should be considered for inclusion in performance standards for ski and snowboard helmets. Halldin et al. [30] used the KTH Oblique Test Rig to evaluate the performance of alpine helmets with the

Multi-directional Impact Protection System (MIPS), which features a low-friction layer inside the helmet that allows multi-directional relative movement of 10–15 mm between the helmet and the head. For a resultant impact speed of 7.4 m/s and an impact angle of approximately 30°, the MIPS helmet reduced peak angular acceleration and velocity by 38% and 23%, respectively, compared to a standard helmet. Using a 45° anvil to induce oblique impacts from vertical drop tests, DiGacomo et al. [31] compared a standard alpine helmet to helmets with rotation-damping systems (RDS): MIPS and WaveCel. The latter comprises a cellular structure that collapses to provide rotational attenuation. It was found that the alpine helmets with RDS reduced peak angular headform velocity and acceleration compared to the standard alpine helmet. Both Halldin et al. [30] and DiGacomo et al. [31] tested the helmets against rigid anvils covered in grip tape, which provides a consistent surface but does not represent an impact on the snow.

To the authors' knowledge, no study has used an oblique impact test rig to bridge the knowledge gap between real helmeted impacts onto alpine snow slopes and laboratory helmet impacts onto rigid surfaces. Therefore, the aim of the current study was to develop a method to assess the performance of alpine helmets for radial and oblique impacts onto snow surfaces in a laboratory setting and compare peak headform kinematics across headform conditions. For radial impacts, it was hypothesised that helmeted tests have lower peak linear acceleration compared to unhelmeted tests. For oblique impacts, it was hypothesised that the helmeted tests with RDS would reduce peak linear acceleration compared to standard helmets.

2. Materials and Methods

2.1. Snow Sample Collection

Snow sample boxes were constructed using laminated particleboard with inner length, width and depth dimensions of 400, 200 and 100 mm, respectively. Snow samples were collected at Flottsbro Alpin, which is a small ski resort located in Stockholm County, Sweden. Flottsbro Alpine comprises 4 km of ski trails, which are covered by snow from high- and low-pressure snowmaking cannons. A groomed area on one of the main Flottsbro slopes was selected, and samples of snow were excavated manually using a shovel. Initially, the samples were intentionally larger than the sample boxes and were subsequently cut to the correct size and placed into the sample boxes. Particular attention was paid to maintaining the groomed top surface of each snow sample as much as possible. The time and ambient temperature were recorded for each collection day. Snow samples were transported 15 min to the laboratory, and non-frozen samples were tested within 15 min of delivery to the laboratory. To simulate hard icy snow, as per previous studies [18–21], snow samples were placed in an industrial freezer set to −40 °C for two hours prior to testing.

2.2. Helmets

Three different helmet models were tested for oblique impacts: a ski racing helmet, a recreational alpine sports helmet with RDS and the same recreational alpine sports helmet make and model without RDS. The RDS comprised a low-friction layer between the inner liner and the comfort liner of the helmet. Therefore, during an oblique impact, the bulk of the helmet (i.e., outer shell and inner liner) moves relative to the comfort liner that couples to the headform (Figure 1). The crown of the ski racing helmet shell was smooth with only small circular vent holes at the rear of the helmet, whereas the recreational alpine sports helmets, both with and without RDS, had large vent holes at the crown and rear of the helmet (Figure 2).

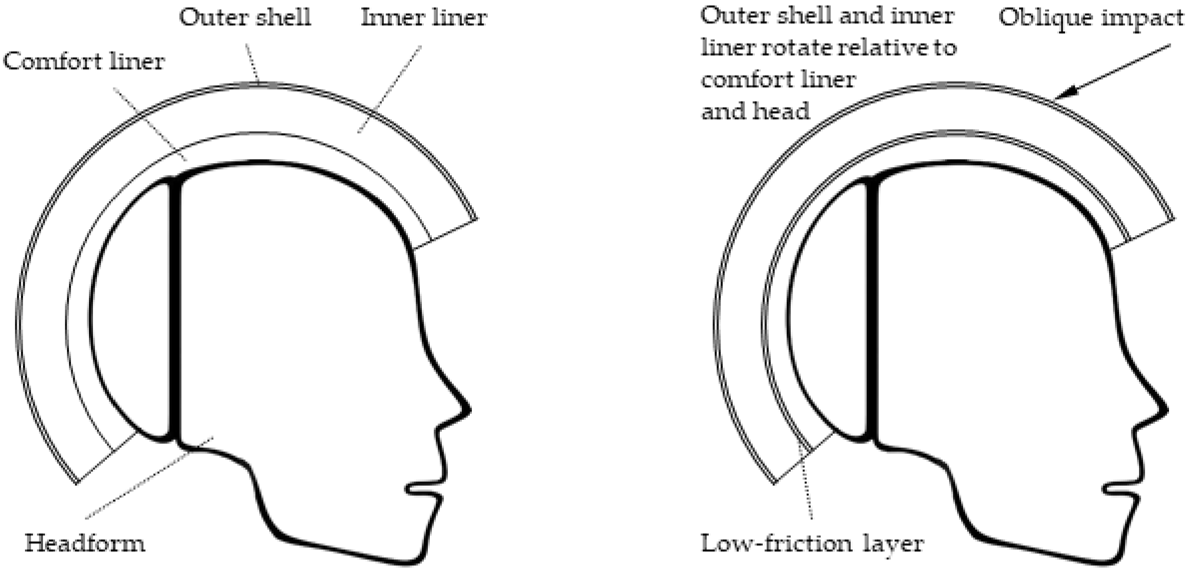

Figure 1. Cross sections of a traditional helmet (**left**) and a helmet with RDS (**right**).

Figure 2. Rear views of the ski racing helmet (**left**) and recreational alpine sports helmet (**right**). Note that the recreational alpine sports helmet, both with and without RDS, had the same shell design.

2.3. Impact Testing

Impact testing was performed using the KTH Oblique Test Rig [32], which comprises a vertical drop tower and a horizontal sled driven by a pneumatic piston (Figure 3). A 50th percentile Hybrid III headform, either helmeted or unhelmeted, was held in position by arm-mounted pneumatic pistons with rubber stoppers at a specific drop height. The firing of the pneumatic piston driving the sled and the release of the pneumatic pistons holding the headform or helmet were timed so that the headform or helmet impacts the sled. The headform comprised a 3-3-3 array of triaxial accelerometers mounted at the centre of gravity, which recorded linear accelerations at a sampling rate of 20 kHz. An aluminium flag of known dimensions was mounted to the sled and triggered recording (5 ms pre-trigger and 45 ms post-trigger) when it passed through a light gate mounted to the horizontal rails; angular acceleration was calculated algebraically at 20 kHz. Linear and angular acceleration data were filtered as per SAE International J211 using a 4-pole Butterworth low pass filter (channel frequency class 1000, 3 dB limit frequency 1650 Hz).

All tests were filmed in high-speed video from a stationary camera position to capture a side view of the impact at a frame rate of 1000 s^{-1}.

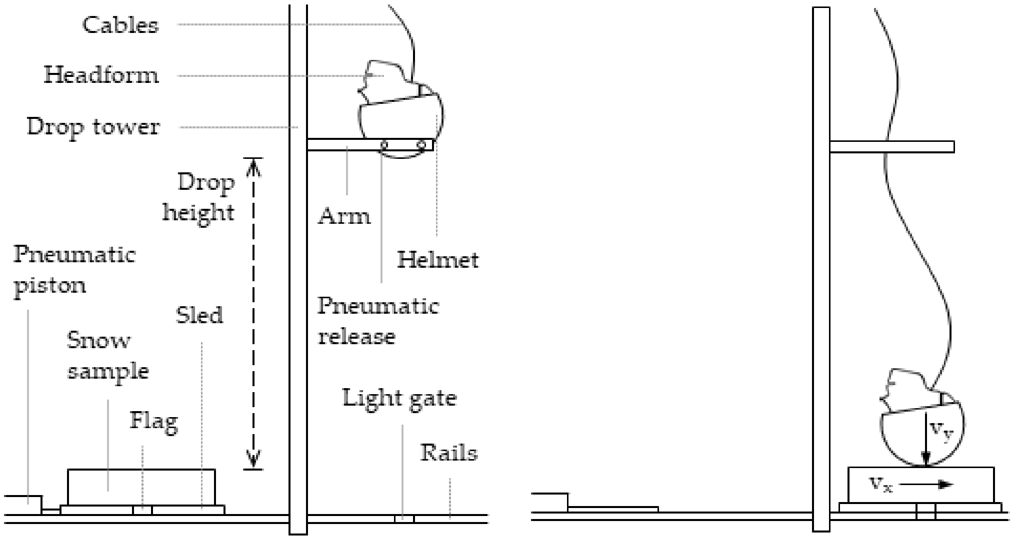

Figure 3. KTH Oblique Test Rig in the initial position (**left**) and at the time of impact (**right**). v_y: vertical velocity calculated from drop height. v_x: horizontal velocity calculated from light gate.

2.3.1. Radial Impacts

For radial impacts, the sled was stationary and positioned at the base of the vertical drop tower. The snow sample box was clamped to the sled. Three exclusive sites, i.e., front, middle and rear, were impacted per snow sample. Prior to each test, the headform was oriented so that the crown would impact the snow surface. Drop carriage heights of 0.85 and 1.5 m were tested, which correspond to impact speeds of 4.1 and 5.4 m/s, respectively. The latter height is of interest as the European [14] and Canadian [15] alpine helmet standards require drop tests from 1.5 m onto a flat anvil. Three conditions were tested: bare headform, beanie and helmet. The beanie was a black acrylic knit in a size medium and representative of a typical beanie worn during alpine sports. The helmets tested in the radial impacts were all recreational alpine sports helmets with no RDS, in medium and large sizes.

2.3.2. Oblique Impacts

For oblique impacts, the sled was pneumatically driven along the horizontal rails and synchronised with the release of the drop carriage so that the helmet impacted the snow in the snow sample box. Horizontal speed was measured when the flag of known dimensions mounted to the sled passed through the light gate. The horizontal target speed was 6 m/s. For a vertical velocity of 4.1 m/s (0.85 m drop height), the resultant velocity was 7.3 m/s at an impact angle of 34° to the horizontal. For a vertical velocity of 5.4 m/s (1.5 m drop height), the resultant velocity was 8.1 m/s at an impact angle of 42° to the horizontal. Both angles are within the range previously reported in alpine sports: 25–57° [33]. Due to the setup time for oblique impacts, only snow samples that were kept in the freezer for two hours were tested, and only a single impact was performed per snow sample. Three different helmet models were tested for oblique impacts: a recreational alpine sports helmet with RDS, the same recreational alpine sports helmet make and model with no RDS and a ski racing helmet.

2.4. Data Analysis

Resultant kinematics were calculated by adding the component data for the three unique axes in quadrature. For the radial impact tests, multiple linear regression analyses were used to identify significant ($p < 0.05$) associations between the test conditions (independent variables) and peak linear acceleration (dependent variable). Test conditions (i.e., snow sample collection time, freezer and headform condition) were coded as categorical variables. For the oblique impact tests, multiple linear regression was used to identify significant ($p < 0.05$) associations between the helmet models (independent variables) and peak angular acceleration (dependent variable). Helmet models (i.e., ski racing helmet, recreational alpine sports helmet with no RDS and recreational alpine sports helmet with RDS) were coded as categorical variables. Linearity for the categorical independent variables was assumed, and standard multiple linear regression diagnostics were performed for the normality, homoscedasticity and multicollinearity assumptions.

3. Results

Snow sample collection and testing were completed over two non-consecutive days. The first collection was made at 09:00 in the morning when the ambient temperature was 2 °C. The second collection was made at 09:00 in the morning when the ambient temperature was 6 °C, and the third collection was made later that same day at 12:00 noon when the ambient temperature was 12 °C.

A total of 15 vertical drop tests were conducted with up to two repeats per condition (Table 1). For the snow samples collected in the morning that was not placed in the freezer, all tests resulted in similar mean peak linear headform accelerations, ranging from 77 to 82 *g*, regardless of headform condition. Mean peak linear headform acceleration was significantly ($p = 0.005$) lower for snow samples collected at noon compared to snow samples collected in the morning (Table 2). For tests of the large-size helmet, the frozen snow sample resulted in a higher mean peak linear headform acceleration when compared to the non-frozen snow sample, but the result was non-significant ($p = 0.120$).

Table 1. Peak linear headform accelerations for vertical drop tests from 0.85 m onto snow samples.

Snow Sample Collection	Ambient Temperature [°C]	Freezer Time [Hours]	Headform Condition	*N*	Peak Linear Headform Acceleration [*g*]		
					Mean	SD	CV
Morning	2–6	0	Bare	1	81.7		
			Beanie	2	77.4	6.3	8.1%
			Helmet (M)	3	80.2	15.6	19.4%
			Helmet (L)	3	80.2	8.8	11.0%
		2	Helmet (L)	3	96.1	13.0	13.6%
Noon	12	0	Bare	1	34.1		
			Beanie	2	50.1	0.5	1.1%

SD: standard deviation. CV: coefficient of variation. M: medium size. L: large size.

Table 2. Multiple linear regression of peak linear headform accelerations for vertical drop tests.

	Peak Linear Headform Acceleration [*g*]		
	Coefficient	Standard Error	*p*-Value
Intercept	80.2	6.6	<0.001
Noon	−34.0	9.3	0.005
Freezer	15.9	9.3	0.120
Bare	−5.3	11.4	0.654
Beanie	0.6	9.8	0.954
Medium	−0.01	9.3	0.999

Intercept was a large-size helmet impacted onto a snow sample collected in the morning that was not placed in the freezer. R^2 (adjusted): 67.0%. F-statistic: 6.687 ($p = 0.007$).

For the snow samples collected at noon, large amounts of snow were displaced during a test; therefore, only one test was performed per sample resulting in a total of three tests. The first drop test from 1.5 m, which corresponds to an impact speed of 5.4 m/s, displaced a large amount of snow from a sample collected in the morning and impacted the base of the sample box. Therefore, this test was excluded, and no further tests were performed from the 1.5 m drop height.

A total of six oblique impact tests were conducted, with one repeat per condition (Figure 4). The mean horizontal sled velocity, as measured by the light gate, was 6.0 m/s (SD: 0.1 m/s). The recreational alpine sports helmet with no RDS had the highest mean peak angular headform acceleration of 7291 rad/s^2. The recreational alpine sports helmet with RDS had the lowest mean peak angular headform acceleration (4056 rad/s^2), which was significantly (p = 0.002) lower than the value for the helmet with no RDS. The ski racing helmet had a mean peak angular headform acceleration of 4884 rad/s^2, which was significantly (p = 0.006) lower than the recreational alpine sports helmet with no RDS.

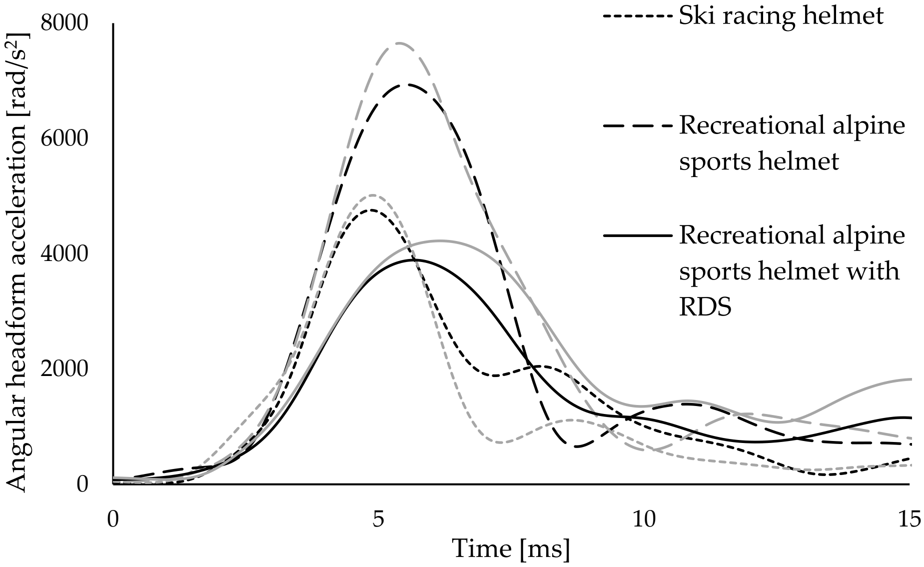

Figure 4. Time-histories of angular headform acceleration for helmeted oblique impacts tests onto frozen snow samples. Traces in grey depict time histories of repeat tests. Traces were time aligned for comparison.

4. Discussion

Head injuries are common in alpine sports despite increases in helmet use over recent decades. Recent studies have found that alpine helmets reduce the risk of focal injuries associated with radial impacts, such as skull fracture, but are less effective in reducing the risk of diffuse injuries associated with rotation, such as intracranial haemorrhage. Current helmet standards involve drop tests onto rigid anvils, but there is a need to evaluate the performance of alpine helmets with more realistic impacts. Therefore, the current study developed a method to assess the performance of alpine helmets for radial and oblique impacts onto snow surfaces in a laboratory setting and compared peak headform kinematics across headform conditions.

For oblique impacts, the recreational alpine sports helmet with RDS significantly (p = 0.002) reduced mean peak angular acceleration compared to the same helmets with no RDS by approximately 44%, which supports the findings of previous studies that compared helmet models during oblique impacts to rigid anvils [30,31]. Typical helmets are optimised to reduce the linear acceleration of the head [18], which is associated with focal head injuries, such as skull fractures. This is likely due to alpine helmet standards requiring helmets to be drop tested on flat anvils with only linear acceleration pass criteria. Currently, no alpine helmet standard includes an oblique impact test with rotational criteria.

However, there are efforts to revise helmet standards [34–36], including alpine helmet standards [30,33], to include rotational testing components. For example, several current bicycle and motorcycle helmet standards involve rotational testing. The American Society for Testing and Materials (ASTM) has developed a standard test method for measuring impact attenuation characteristics of helmets induced under rotational loading using an incline anvil; however, this has yet to be incorporated into the ASTM standard specification for helmets used for recreational snow sports. Such rotational testing is required to be representative of sports-specific impacts; therefore, developing a foam that behaves similarly to snow during dynamic impacts would allow for a repeatable test method suitable for use in alpine helmet standards. In addition, Virginia Tech recently published the Summation of Tests for the Analysis of Risk (STAR) protocol for snow sport helmets, which comprises a rotational testing component [37].

The ski racing helmet also significantly ($p = 0.006$) reduced mean peak angular acceleration compared to the recreational alpine sports helmet with no RDS by approximately 33%. This finding may be attributed to the difference in vent location on the helmet shells. The crown of the ski racing helmet shell was smooth with only small circular vent holes at the rear of the helmet, whereas the recreational alpine sports helmets, both with and without RDS, had large vent holes at the crown and rear of the helmet. The crown of the helmets was the target impact site for the tests in the current study; however, impacting a different site (e.g., rear) may have resulted in different peak angular accelerations. Helmets are typically designed with smooth outer shells, which lowers the friction between the helmet and the impacted surface and, therefore, decreases the tangential forces and angular acceleration of the head [34,38]. Substantial variations in peak angular headform acceleration have been previously reported in oblique impact testing of motorcycle helmets, which was attributed to interactions between the helmet vent and the high friction surface of the angled anvil [39].

For the radial impacts, snow sample collection time and ambient temperature were found to influence mean peak linear headform acceleration, which was significantly ($p = 0.005$) lower for snow samples collected at noon compared to samples collected in the morning. The relatively higher ambient temperature during the noon collection likely softened the snow. For tests of the large-size helmet, the frozen snow sample resulted in a higher mean peak linear headform acceleration when compared to the non-frozen snow sample, but the result was non-significant ($p = 0.120$). These findings can be explained by considering snow as a foam, which can absorb energy more than a rigid or semi-rigid surface, and support results from previous experimental [18–21] and computational [24,25] studies. Recent studies have validated computational models of snow as a foam using a rigid body [24,25] and finite element techniques [23]. For the snow samples collected in the morning with no freezing, all tests resulted in similar peak linear headform accelerations regardless of headform condition. A drop height of 0.85 m is likely not high enough to cause the snow to “bottom out”, similar to a foam material [38], and engage the energy-absorbing inner liner of the helmet. It is hypothesised that higher impact speeds increase the reduction in peak linear headform acceleration for helmeted tests relative to unhelmeted tests. However, when a drop test from 1.5 m was performed in the current study, which corresponds to an impact speed of 5.4 m/s, a large amount of snow was displaced from a sample box. The displacement of snow resulted in the headform impacting the base of the sample box. It is unknown if this test is representative of an impact on the soft snow layer that is covering an icy base layer. No further tests were performed from this height; therefore, field tests on actual snow slopes or laboratory tests using deeper snow samples are required to investigate higher drop heights, such as 1.5 m as per the European [14] and Canadian [15] alpine helmet standards.

Although DeMarco et al. [40] previously tested “beanie helmets”, which are non-approved motorcycle helmets with hard shells, the traditional beanie in the current study was an acrylic knit cap with no shell. Recent advancements in material science have led to the development of a helmet without an outer shell that incorporates a layer of non-

Newtonian shear thickening fluid (STF) as part of the inner liner [41]. The viscosity of an STF increases when the shear rate increases; therefore, during an impact, the STF layer is flexible during general wear but hardens when the helmet is impacted. The helmet is covered with a knitted layer, which makes it look like a beanie; however, it incorporates several features of a helmet, such as a retention system and an inner liner of energy-absorbing foam. To the authors' knowledge, no previous studies have assessed the impact attention potential of traditional beanies. Interestingly, Fukuda et al. [42,43] found that beanie use was significantly associated with reduced head injuries in snowboarding; however, the odds ratio for the effect of beanie use on serious head injuries was non-significant after adjusting for jumping.

The current study has several limitations, mainly the quality and repeatability of the snow samples. Although the snow samples were collected from the same location, there may have been differences in structure for various reasons. For example, a vehicle may have driven over one section of the collection site. Efforts were also made to replicate the timing between collection and testing, but slight variations may have resulted in snow samples being exposed to different temperatures. Similar limitations were identified in a previous study by Dressler et al. [21]. In addition, there was concern regarding moisture from the melted snow in the laboratory, where much of the equipment is susceptible to water damage. For example, the horizontal rails on which the sled translates needed to be inspected and dried after each test so that the speed of the sled remained consistent. Ideally, oblique impact tests would be performed in situ to avoid consistency issues found in the current study, which include varying ambient temperatures, melting during transport and edge effects from the sample boxes. However, Kleiven et al. [23] previously drop-tested a helmeted headform manually onto a snow slope, which involved issues such as wind causing unwanted rotations during pre-impact free-fall. Stuart et al. [44] developed an impact testing apparatus for testing helmets on snow surfaces, which employs a compression spring to accelerate a headform carriage that releases just prior to impact. Laboratory validation impacts onto a low-density foam surface were performed, which demonstrated good repeatability; however, tests onto snow slopes have yet to be reported. Although the Hybrid III ATD headform used in the current study represents the average mass and geometry of the 50th percentile male head, no neckform was used, and the mass of the torso was not approximated. Therefore, the test setup was appropriate to compare relative kinematics across conditions but was not intended to represent reconstructions of actual falls onto ski slopes.

5. Conclusions

The current study found that the recreational alpine sports helmet with RDS and the ski racing helmet with a smooth outer shell significantly reduced mean peak angular acceleration compared to helmets with no RDS in oblique impact tests. Snow samples collected during later times with higher ambient temperatures were associated with significantly lower mean peak linear headform accelerations for radial impact tests. The current study helps to bridge the knowledge gap between real helmet impacts on alpine snow slopes and laboratory helmet impacts onto rigid surfaces, which is the current method to assess the impact attenuation performance of helmets for alpine sports. In addition, the current study informs stakeholders in standards tests for alpine sports helmets regarding the potential to include oblique impact performance criteria. Future studies should continue to explore oblique impact tests in situ on snow slopes and use foams with similar material properties to snow in laboratory oblique impact tests to avoid the consistency issues identified in the current study.

Author Contributions: Conceptualization, D.A.P., P.H., S.K. and A.S.M.; methodology, D.A.P. and P.H.; formal analysis, D.A.P. and R.M.; investigation, D.A.P., R.M. and P.H.; resources, P.H. and S.K.; writing—original draft preparation, D.A.P. and R.M.; writing—review and editing, P.H., S.K. and A.S.M.; supervision, S.K. and A.S.M. All authors have read and agreed to the published version of the manuscript.

Funding: D.A.P. was funded by an Endeavour Research Fellowship from the Australian Government. S.K. and R.M. were supported by research funds from Tillväxtverket (Swedish Agency for Economic and Regional Growth) for the project Augmented Sports and European Union's Horizon 2020 research and innovation program under the Marie-Curie Grant Agreement No. 642662.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are available upon reasonable request.

Acknowledgments: The authors would like to thank Flottsbro Alpin ski resort for allowing snow sample collection. At the time of the study, D.A.P. and A.S.M. were affiliated with the Australian Centre for Research into Injury in Sport and its Prevention (ACRISP), which is one of the International Olympic Committee Research Centres for Prevention of Injury and Protection of Athlete Health.

Conflicts of Interest: P.H. is the Chief Science Officer and Co-Founder of MIPS AB (Stockholm, Sweden).

References

1. McBeth, P.B.; Ball, C.G.; Mulloy, R.H.; Kirkpatrick, A.W. Alpine Ski and Snowboarding Traumatic Injuries: Incidence, Injury Patterns, and Risk Factors for 10 Years. *Am. J. Surg.* **2009**, *197*, 560–563. [CrossRef] [PubMed]
2. Steenstrup, S.E.; Bere, T.; Bahr, R. Head Injuries Among FIS World Cup Alpine and Freestyle Skiers and Snowboarders: A 7-Year Cohort Study. *Br. J. Sport. Med.* **2014**, *48*, 41–45. [CrossRef] [PubMed]
3. Ehrnthaller, C.; Kusche, H.; Gebhard, F. Differences in Injury Distribution in Professional and Recreational Snowboarding. *Open Access J. Sport. Med.* **2015**, *6*, 109–119. [CrossRef]
4. Patton, D.A.; McIntosh, A.S.; Hagel, B.E.; Krosshaug, T. A Review of Head Injury and Impact Biomechanics in Recreational Skiing and Snowboarding. *Muscle Ligaments Tendons J.* **2020**, *10*, 211–232. [CrossRef]
5. Russell, K.; Christie, J.; Hagel, B. The Effect of Helmets on the Risk of Head and Neck Injuries Among Skiers and Snowboarders: A Meta-Analysis. *Can Med. Assoc. J.* **2010**, *182*, 333–340. [CrossRef]
6. Cusimano, M.D.; Kwok, J. The Effectiveness of Helmet Wear in Skiers and Snowboarders: A Systematic Review. *Br. J. Sport. Med.* **2010**, *44*, 781–786. [CrossRef]
7. Haider, A.H.; Saleem, T.; Bilaniuk, J.W.; Barraco, R.D. An Evidence Based Review: Efficacy of Safety Helmets in Reduction of Head Injuries in Recreational Skiers and Snowboarders. *J. Trauma Acute Care Surg.* **2012**, *73*, 1340–1347. [CrossRef]
8. Baschera, D.; Hasler, R.M.; Taugwalder, D.; Exadaktylos, A.; Raabe, A. Association Between Head Injury and Helmet Use in Alpine Skiers: Cohort Study from a Swiss Level I Trauma Center. *J. Neurotrauma* **2015**, *32*, 557–562. [CrossRef]
9. Sulheim, S.; Ekeland, A.; Holme, I.; Bahr, R. Helmet Use and Risk of Head Injuries in Alpine Skiers and Snowboarders: Changes After an Interval of One Decade. *Br. J. Sport. Med.* **2017**, *51*, 44–50. [CrossRef]
10. Milan, M.; Jhajj, S.; Stewart, C.; Pyle, L.; Moulton, S. Helmet Use and Injury Severity Among Pediatric Skiers and Snowboarders in Colorado. *J. Pediatr. Surg.* **2017**, *52*, 349–353. [CrossRef]
11. Bailly, N.; Laporte, J.D.; Afquir, S.; Masson, C.; Donnadieu, T.; Delay, J.B.; Arnoux, P.J. Effect of Helmet Use on Traumatic Brain Injuries and Other Head Injuries in Alpine Sport. *Wilderness Environ. Med.* **2018**, *29*, 151–158. [CrossRef]
12. Porter, E.D.; Trooboff, S.W.; Haff, M.G.; Cooros, J.C.; Wolffing, A.B.; Briggs, A.; Rhynhart, K.K.; Crockett, A.O. Helmet Use is Associated with Higher Injury Severity Scores in Alpine Skiers and Snowboarders Evaluated at a Level I Trauma Center. *J. Trauma Acute Care Surg.* **2019**, *87*, 1205–1213. [CrossRef] [PubMed]
13. *ASTM F2040*; Standard Specification for Helmets Used for Recreational Snow Sports. American Society for Testing and Materials: West Conshohocken, PA, USA, 2011.
14. *EN 1077*; European Committee for Standardization, Helmets for Alpine Skiers and Snowboarders. European Committee for Standardization: Brussels, Belgium, 2007.
15. *CSA Z263.1*; Canadian Standards Association, Recreational Alpine Skiing and Snowboarding Helmets. Canadian Standards Association: Toronto, ON, Canada, 2015.
16. *Snell RS-98*; Snell Memorial Foundation, Recreational Skiing and Snowboarding. Snell Memorial Foundation: North Highlands, CA, USA, 1998.
17. *Snell S-98*; Snell Memorial Foundation, Skiing and Other Winter Activities. Snell Memorial Foundation: North Highlands, CA, USA, 1998.
18. Scher, I.S.; Richards, D.; Carhart, M. Head Contact After Catching an Edge: An Examination of Snowboarding Helmets. In proceedings of the 16th International Society of Skiing Safety Conference, Niigata, Japan, 2005. *Knee Surg. Sport. Traumatol. Arthrosc.* **2006**, *14*, 97.
19. Scher, I.S.; Richards, D.; Carhart, M. Head Injury in Snowboarding: Evaluating the Protective Role of Helmets. *J. ASTM Int.* **2006**, *3*, JAI14203. [CrossRef]
20. Richards, D.; Carhart, M.; Scher, I.; Thomas, R.; Hurlen, N.; Johnson, R.J.; Shealy, J.E.; Langran, M. Head Kinematics During Experimental Snowboard Falls Implications for Snow Helmet Standards. *J. ASTM Int.* **2008**, *5*, JAI101406. [CrossRef]

21. Dressler, D.; Richards, D.; Bates, E.; Van Toen, C.; Cripton, P. Head and Neck Injury Potential with and Without Helmets During Head-First Impacts on Snow. In Proceedings of the 19th International Symposium on Skiing Trauma and Safety, Keystone, CO, USA, 1–7 May 2011; Johnson, R.J., Shealy, J.E., Greenwald, R.M., Scher, I.S., Eds.; ASTM International: West Conshohocken, PA, USA, 2012; STP104525; pp. 235–249.
22. Yamazaki, J.; Gilgien, M.; Kleiven, S.; McIntosh, A.S.; Nachbauer, W.; Muller, E.; Bere, T.; Bahr, R.; Krosshaug, T. Analysis of a Severe Head Injury in World Cup Alpine Skiing: A Case Report. *Med. Sci. Sport Exerc.* **2015**, *47*, 1113–1118. [CrossRef]
23. Kleiven, S.; Halldin, P. Head Impact Biomechanics in Ski Related Accident. In proceedings of the 4th International Conference on Concussion in Sport, Zurich, Switzerland, 2012. *Br. J. Sport. Med.* **2013**, *47*, e1.53.
24. Bailly, N.; Llari, M.; Donnadieu, T.; Masson, C.; Arnoux, P.J. Head Impact in a Snowboarding Accident. *Scand. J. Sci. Med. Sport.* **2017**, *27*, 964–974. [CrossRef]
25. Bailly, N.; Llari, M.; Donnadieu, T.; Masson, C.; Arnoux, P.J. Numerical Reconstruction of Traumatic Brain Injury in Skiing and Snowboarding. *Med. Sci. Sport Exerc.* **2018**, *50*, 2322–2329. [CrossRef]
26. Nakaguchi, H.; Fujimaki, T.; Ueki, K.; Takahashi, M.; Yoshida, H.; Kirino, T. Snowboard Head Injury: Prospective Study in Chino, Nagano, for Two Seasons from 1995 to 1997, in 58th Annual Meeting of the American Association for the Surgery of Trauma. *J. Trauma Acute Care Surg.* **1999**, *46*, 1066–1069. [CrossRef]
27. Fukuda, O.; Takaba, M.; Saito, T.; Endo, S. Head Injuries in Snowboarders Compared with Head Injuries in Skiers: Prospective Analysis of 1076 Patients from 1994 to 1999 in Niigata, Japan. *Am. J. Sport. Med.* **2001**, *29*, 437–440. [CrossRef] [PubMed]
28. Nakaguchi, H.; Tsutsumi, K. Mechanisms of Snowboarding-Related Severe Head Injury: Shear Strain Induced by the Opposite-Edge Phenomenon. *J. Neurosurg.* **2002**, *97*, 542–548. [CrossRef] [PubMed]
29. Koyama, S.; Fukuda, O.; Hayashi, N.; Endo, S. Differences in Clinical Characteristics of Head Injuries to Snowboarders by Skill Level. *Am. J. Sport. Med.* **2011**, *39*, 2656–2661. [CrossRef]
30. Halldin, P.; Kleiven, S. The Development of Next Generation Test Standards for Helmets. In Proceedings of the 1st International Conference on Helmet Performance and Design, London, UK, 15 February 2013; pp. 1–8.
31. DiGiacomo, G.; Tsai, S.; Bottlang, M. Impact Performance Comparison of Advanced Snow Sport Helmets with Dedicated Rotation-Damping Systems. *Ann. Biomed. Eng.* **2021**, *49*, 2805–2813. [CrossRef] [PubMed]
32. Aare, M.; Halldin, P. A New Laboratory Rig for Evaluating Helmets Subject to Oblique Impacts. *Traffic Inj. Prev.* **2003**, *4*, 240–248. [CrossRef] [PubMed]
33. Steenstrup, S.E.; Mok, K.-M.; McIntosh, A.S.; Bahr, R.; Krosshaug, T. Head Impact Velocities in FIS World Cup Snowboarders and Freestyle Skiers: Do Real-life Impacts Exceed Helmet Testing Standards? *Br. J. Sport. Med.* **2018**, *52*, 32–40. [CrossRef]
34. McIntosh, A.S.; Andersen, T.E.; Bahr, R.; Greenwald, R.M.; Kleiven, S.; Turner, M.; Varese, M.; McCrory, P.R. Sports Helmets Now and in the Future. *Br. J. Sport. Med.* **2011**, *45*, 1258–1265. [CrossRef]
35. Pang, T.Y.; Thai, K.T.; McIntosh, A.S.; Grzebieta, R.; Schilter, E.; Dal Nevo, R.; Rechnitzer, G. Head and Neck Responses in Oblique Motorcycle Helmet Impacts: A Novel Laboratory Test Method. *Int. J. Crashworthiness* **2011**, *16*, 297–307. [CrossRef]
36. Mcintosh, A.S.; Lai, A.; Schilter, E. Bicycle Helmets: Head Impact Dynamics in Helmeted and Unhelmeted Oblique Impact Tests. *Traffic Inj. Prev.* **2013**, *14*, 501–508. [CrossRef]
37. Keim, S.; Begonia, M.T.; Kieffer, E.E.; Rowson, S. *Snow Sport Helmet STAR Protocol*; Virginia Tech Helmet Lab: Blacksburg, VA, USA, 2022.
38. Newman, J.A. Biomechanics of Human Trauma: Head Protection. In *Accidental Injury: Biomechanics and Prevention*; Nahum, A., Melvin, J., Eds.; Springer: New York, NY, USA, 1993; pp. 292–310.
39. Juste-Lorente, Ó.; Maza, M.; Piccand, M.; López-Valdés, F.J. The Influence of Headform/Helmet Friction on Head Impact Biomechanics in Oblique Impacts at Different Tangential Velocities. *Appl. Sci.* **2021**, *11*, 11318. [CrossRef]
40. DeMarco, A.L.; Chimich, D.D.; Gardiner, J.C.; Nightingale, R.W.; Siegmund, G.P. The Impact Response of Motorcycle Helmets at Different Impact Severities. *Accid. Anal. Prev.* **2010**, *42*, 1778–1784. [CrossRef] [PubMed]
41. Bloodworth-Race, S.; Critchley, R.; Hazael, R.; Peare, A.; Temple, T. Testing the Blast Response of Foam Inserts for Helmets. *Heliyon* **2021**, *7*, e06990. [CrossRef]
42. Fukuda, O.; Hirashima, Y.; Origasa, H.; Endo, S. Characteristics of Helmet or Knit Cap Use in Head Injury of Snowboarders—Analysis of 1,190 Consecutive Patients. *Neurol. Med. Chir.* **2007**, *47*, 491–494. [CrossRef] [PubMed]
43. Fukuda, O.; Koyama, S.; Endo, S. Head Injuries in Skiers and Snowboarders. *J. Jpn. Soc. Clin. Sport. Med.* **2008**, *16*, 165–171.
44. Stuart, C.A.; Cripton, P. Design of a Novel Helmet Impact Testing Apparatus Representative of Snow Sports Head Injury. In Proceedings of the International Research Council on the Biomechanics of Impact Conference, IRCOBI, Antwerp, Belgium, 13–15 September 2017; pp. 213–214.