The Implications of Surface Friction on Snowsport Helmet Oblique Impact Kinematics

Nicole E-P. Stark[1], Andrew Calis[3], Matthew Wood[1], Summer Blue Piwowarski[1], Kristin Dingelstedt[1], Mark Begonia[2], and Steve Rowson[1]
[1] Biomedical Engineering and Mechanics, Virginia Tech; [2] Institute for Critical Technology and Applied Science (ICTAS), Virginia Tech

ABSTRACT

Head injuries account for 15% of snowsport-related injuries, and the majority of head impacts occur against ice or snow, low friction surfaces. Therefore, this study aimed to evaluate how surface friction affects snowsport helmets' oblique impact kinematics. Ten helmet models were impacted using an oblique drop tower with a 45-degree anvil and NOCSAE headform, at three locations, two surface friction conditions, and a drop speed of 5.0 m/s. Our findings indicate that friction affects peak linear acceleration, peak rotational acceleration, and peak rotational velocity during helmet impacts, with changes in post-impact rotation and impact response varying by location. Surface friction affects head impact kinematics, underscoring the need for sport-specific lab testing and emphasizing the need for friction-specific and sport-specific testing, particularly for snowsports, where surface conditions like snow and ice can alter kinematics.

INTRODUCTION

Head injuries account for 15% of snowsport-related injuries, but over 40% of cases the treated at trauma centers (Haider et al., 2012; Levy et al., 2002; Wasden et al., 2009). Research indicates snowsport helmets could reduce head injuries by 21%-45% (Weber et al., 2016), although optimizing performance through realistic testing could further reduce injuries. Notably, 65%-70% of snowsport traumatic brain injuries (TBIs) occur against ice or snow, low-friction surfaces (Bailly et al., 2017). Studies have shown that increased surface friction increases rotational kinematics and impact duration but not linear kinematics (Bonugli et al., 2017; Camacho et al., 1999; Petersen et al., 2020). Petersen et al. and Bonugli et al. observed increased rotational kinematics but not linear kinematics due to higher friction, with side impacts being most sensitive to these changes. They also found the rotational direction off the anvil depended upon surface friction (Bonugli et al., 2017; Petersen et al., 2020). These findings underscore the critical role of friction in helmet testing and the need for sport-specific evaluations. Therefore, this study aimed to evaluate how surface friction affects snowsport helmets' oblique impact kinematics.

This paper is a student paper from the 19th Injury Biomechanics Symposium and is published in a special issue of SAE International Journal of Transportation Safety.
It is preliminary work, has not been peer reviewed, and should not be cited because it is a work in progress.

METHODS

Friction Testing

We measured two helmet models' (Lucky Bums and Gyro Ledge MIPS**)** static coefficient of friction (COF) against high-friction (80-grit sandpaper) and low-friction (steel) surfaces using a custom tribometer and methods described by Stark et al. (Stark et al., 2023). 80-grit sandpaper was used to simulate the frictional interface of a helmet striking a high-COF surface, such as pavement. Steel was chosen to replicate the frictional interface of a helmet striking a lower friction surface, such as ice and snow. The Gyro Ledge MIPS helmet was selected as a representative sample of a helmet with a matte finish. The Lucky Bums was chosen as its helmet shell had an outer coating on the material, an outlier of the helmet models tested in the study. All other eight helmet models used in this study had a matte finish (Figure 1).

For each helmet model sample, we conducted a series of four trials against steel and 80-grit sandpaper. The COF was measured using a sample coupon of a helmet shell mounted to the fixed frame of the tribometer. The sample coupon was lowered onto a sled consisting of the frictional interface (80-grit or steel) mounted to a pancake load cell. A normal force of 80 N load was applied to a pancake load cell to a sled interacting with either surface. The tangential force was applied to the sled by a wire passed over a pully connected to an in-line load cell to measure the tangential force applied accurately. Weight was added incrementally until the sled moved, indicating the static COF was overcome. A new coupon was employed for each test to prevent any degradation.

Oblique Impact Testing

Ten helmet models were impacted using an oblique drop tower with a 45-degree anvil and helmeted National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform, at three locations (front, side, rear boss), two COF conditions (high and low), and a drop speed of 5.0 m/s, informed by real-world data (Figure 1) (Keim et al., 2022).

This paper is a student paper from the 19th Injury Biomechanics Symposium and is published in a special issue of SAE International Journal of Transportation Safety.
It is preliminary work, has not been peer reviewed, and should not be cited because it is a work in progress.

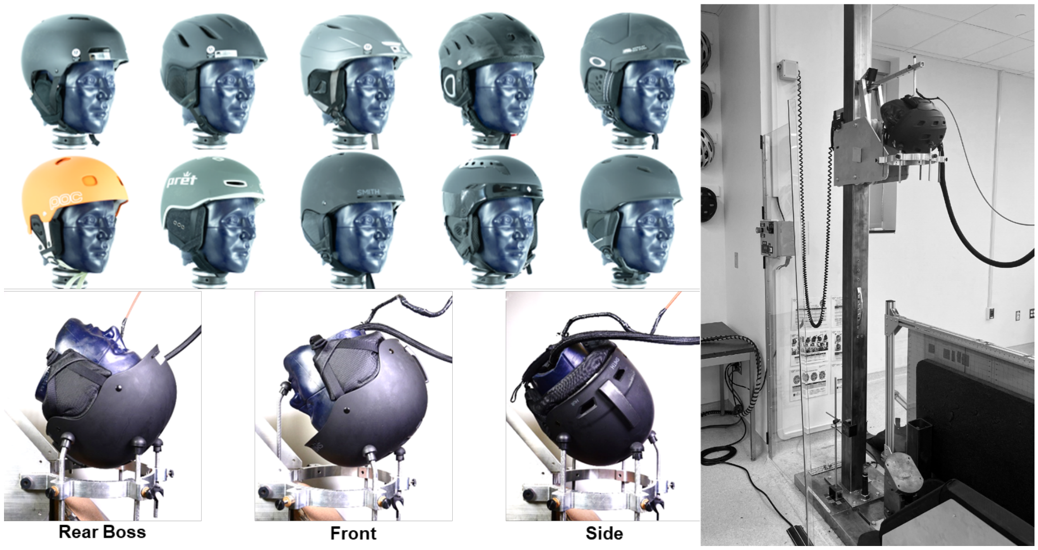

Figure 1: Ten helmet models tested, oblique drop tower, and the three impact locations.

Impact locations were set and confirmed using a dual-axis inclinometer, cross-level laser, and wall-mounted grid to ensure consistent positioning on the support ring of the drop tower. The NOCSAE headform was instrumented with a six-degree-of-freedom sensor package that consisted of three accelerometers (Endevco 7264B-2000, PCB Piezotronics, Depew, NY), and a tri-axial angular rate sensor (ARS) (ARS3 PRO, Diversified Technical Systems, Seal Beach, CA), mounted at the headform center of gravity (CG). No anthropomorphic test device (ATD) neck or effective torso mass is used in this testing, as previous work has suggested that oblique impacts may subject the neck to considerable axial loading, a scenario known to present limited biofidelity for current ATD necks (Bland et al., 2018; Sances et al., 2002). Data were collected at a sampling rate of 20 kHz.

Analysis

Collected data were filtered using a 4-pole phaseless Butterworth low-pass filter with a cutoff frequency of 1650 Hz for accelerometer signals (SAE J211) and 289 Hz for ARS signals. Rotational acceleration was then computed using the five-point central difference method. Resultant peak linear acceleration (PLA), peak rotational velocity (PRV), and peak rotational acceleration (PRA) were extracted from the signals.

Previous studies have shown that the direction of headform spin off the anvil, either clockwise or counterclockwise, can vary with surface friction [8,9]. Peak rotational kinematic values were computed and labeled with a sign based on axis-specific signal analysis. For side and rear-boss impacts, positive values indicate clockwise rotation, and negative values indicate counterclockwise. Conversely, for front impacts, positive values signify counterclockwise rotation, and negative values indicate clockwise. A linear mixed-effect model ($\alpha < 0.05$, lmerTest Package (Kuznetsova et al., 2017)) was used to assess how impact location and friction surface influence PLA, PRA, and PRV data, considering their interaction and accounting for spin

This paper is a student paper from the 19th Injury Biomechanics Symposium and is published in a special issue of SAE International Journal of Transportation Safety.
It is preliminary work, has not been peer reviewed, and should not be cited because it is a work in progress.

direction, with helmet model as a random effect.

We also evaluated the effect of location and friction surface through non-directional magnitude data. The rotational headform response off the anvil can be positive or negative, but many injury predictions only consider magnitude (Rowson & Duma, 2013; Takhounts et al., 2013). A linear mixed-effect models compared location and friction, including helmet type, as a random effect for PLA, PRA, and PRV. Post-hoc comparisons for all linear mixed-effect models were completed using least squares means (lmerTest Package (Kuznetsova et al., 2017)) to evaluate friction level effects across locations. All analysis were completed in R (R Version 4.3.0, RStudio; Boston, Massachusetts, USA).

RESULTS

Overall, helmet shells exhibited a COF of 0.78 ± 0.10 (mean ± standard deviation) against 80-grit sandpaper and COF of 0.27 ± 0.09 against steel. The Lucky Bums helmet, which had a coating on the shell, had a COF of 0.20 ± 0.04 against steel and 0.72 ± 0.03 against sandpaper. The Gyro Ledge MIPS, the matte helmet shell, had a COF of 0.35 ± 0.05 against steel and 0.84 ± 0.11 against sandpaper.

There was a main effect of friction for PLA ($p < 0.001$), which decreased from high-COF to low-COF impacts for all locations (Figure 2), by an average of 26 g. PRA ($p < 0.001$) and PRV ($p < 0.001$) responses varied with friction and impact location for maintained rotation directionally data and A post hoc least squares means analysis was conducted to evaluate the interaction effect (Table 1, Figure 2). Observations on headform spin direction further underscored the influence of model and impact location on helmet behavior.

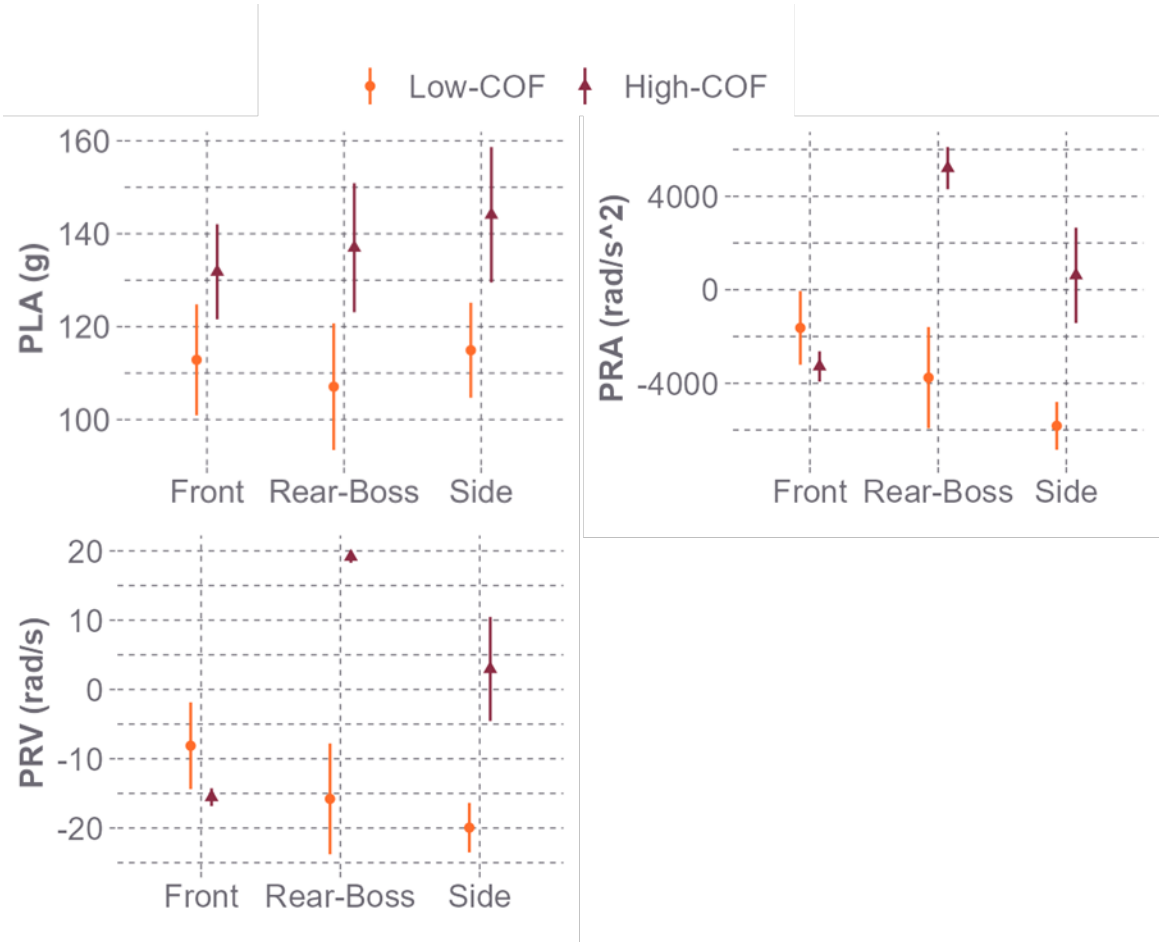

Figure 2: Mean and 95% confidence intervals for directional maintained comparison of PLA, PRA, PRV for high-friction, 80-grit sandpaper, and low-friction, steel.

Table 1: Comparison of PRA and PRV response to friction alteration based on impact location for directional maintain data.

	PRA [rad/s^2]			**PRV [rad/s]**		
	p	Effect	95% CI	p	Effect	95% CI
Front	0.134	1650	-492, 3792	0.06	-7	0, 15
Rear Boss	<0.001	-8965	-11107, -6822	<0.01	-35	-43, -27
Side	<0.001	-6067	-3924, -8209	<0.01	-23	-15, -31

Headform spin direction varied between helmet models and impact locations. In side impacts at low-friction all helmets rolled off the anvil. At high-friction, seven models bounced off, while three rolled off (Figure 3). At the rear-boss location under high-friction conditions, helmets consistently bounced off clockwise; with low friction, all but one model rolled off counterclockwise. For front impacts, only two models exhibited changes in spin direction with different COF levels, whereas eight models showed no change.

This paper is a student paper from the 19th Injury Biomechanics Symposium and is published in a special issue of SAE International Journal of Transportation Safety.
It is preliminary work, has not been peer reviewed, and should not be cited because it is a work in progress.

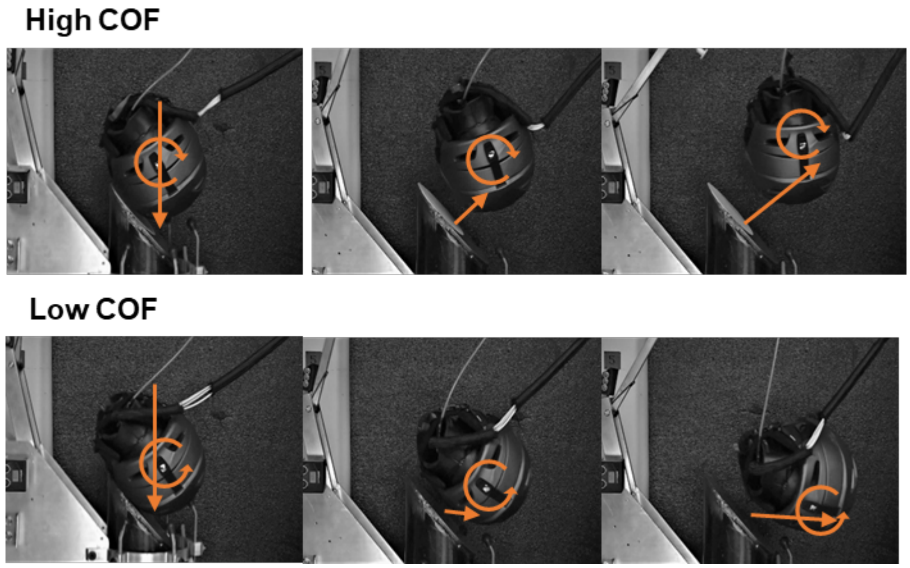

Figure 3: Representative impact sequence for the high-friction and the low-friction impacts with spin direction labled.

Although we identified headform spin direction for each impact, we also evaluated the effect of location and friction surface through non-directional magnitude data. PRA ($p < 0.001$) and PRV ($p < 0.001$) responses varied with friction and impact location for magnitude data (Table 1, Figure 2). The low-COF condition decreased the severity of PRA and PRV for front impacts and the rear boss had similar severity of rotational kinematics regardless of friction condition. However, PRV and PRA increased at the low-friction condition, indicating that the low-friction side impacts were more severe.

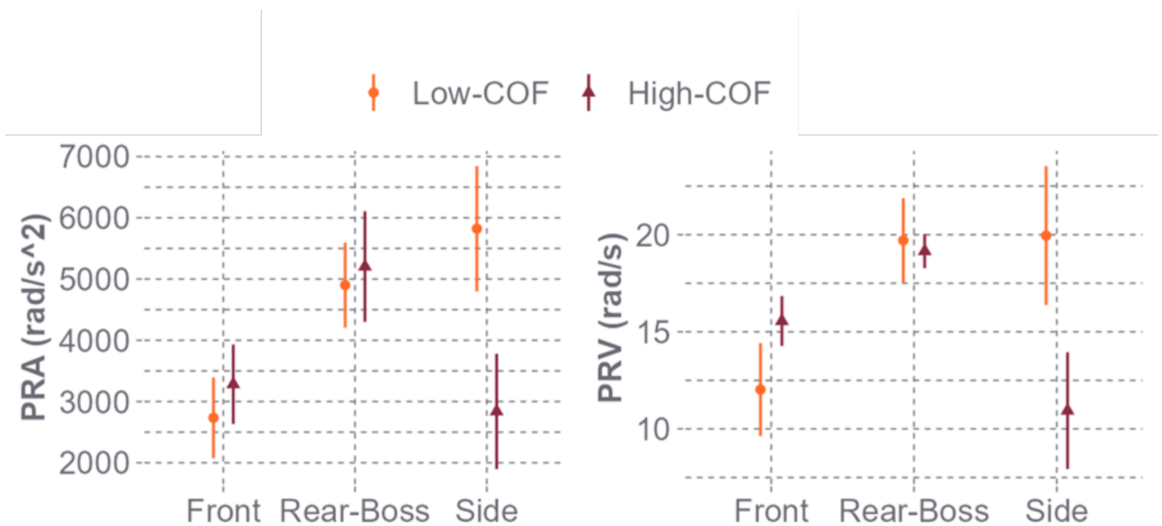

Figure 4: Mean and 95% confidence intervals for magnitude comparison of PLA, PRA, PRV for high-friction, 80-grit sandpaper, and low-friction, steel.

This paper is a student paper from the 19th Injury Biomechanics Symposium and is published in a special issue of SAE International Journal of Transportation Safety.
It is preliminary work, has not been peer reviewed, and should not be cited because it is a work in progress.

Table 2: Comparison of PRA and PRV response to friction alteration based on impact location magnitude data.

	PRA [rad/s²]			PRV [rad/s]		
	p	Effect	95% CI	p	Effect	95% CI
Front	0.357	-548	-1702, 606	0.047	-3.5	-6.9, -0.1
Rear Boss	0.609	-303	-1457, 851	0.750	0.6	-2.8, 3.9
Side	<0.001	2983	1828, 4137	<0.001	9.0	5.6, 12.4

DISCUSSION

Snowsport TBIs often occur against ice or snow, a lower-friction surface than other sports. These results showed that anvil friction affected helmet rotation off the anvil and PLA, PRA, and PRV. Although the magnitudes of PRV and PRA were similar for impacts to the rear boss and front of the helmet, side impacts in low-friction scenarios were distinguished by significantly higher PRA and PRV. Friction influenced rotational kinematics based on impact location, with high-friction impacts showing positive PRV and PRA values as helmets bounced off the anvil, while low-friction impacts led to negative values from helmets skidding off. Notably, at the side impact location, three helmet models displayed negative PRV and PRA under both friction conditions. Conversely, the front impact location did not exhibit the same average change in rotational direction between high- and low-friction conditions, except for two models. These results demonstrate that changes in impact surface friction affect rotational kinematics across different locations. The inconsistencies in the kinematic behavior can be attributed to helmet geometries or the difference in moment of inertia.

The PRV and PRA magnitudes for front and rear-boss impacts showed similarity between high- and low- friction impacts, with changes at the rear-boss and front location attributed to head rotational differences off the anvil. However, side impacts experienced an increase in PRV and PRA for low-friction compared to high-friction impact conditions. This highlights the importance of frictional considerations when performing laboratory impact testing. Additionally, our study indicated consistent COF for helmet shells against 80-grit sandpaper and steel, aligning with prior research, which reported steel COF values ranging from 0.2 to 0.6 and 80-grit sandpaper to be 0.61 ± 0.01 (Bonugli et al., 2017; Petersen et al., 2020). Although we did not directly use ice and snow as low-friction surfaces, previous studies have demonstrated that the COF between snow or ice and polyurethane materials ranges from 0.07 to 0.12 (Nachbauer et al., 2016). Additionally, the possibility of snow indenting upon impact could influence impact kinematics. This variation in frictional properties, coupled with the additional variable of snow indentation, underscores the challenges inherent in accurately simulating real-world snowsport impacts within a laboratory environment.

This paper is a student paper from the 19th Injury Biomechanics Symposium and is published in a special issue of SAE International Journal of Transportation Safety.
It is preliminary work, has not been peer reviewed, and should not be cited because it is a work in progress.

This study's scope was limited to a small sample of helmets at a fixed speed on a steel low-friction surface. Future research should expand to more helmet models, various impact speeds, and compare real ice and snow conditions to steel surfaces.

CONCLUSIONS

Our findings indicate that friction affects PLA, PRA, and PRV during helmet impacts, with changes in post-impact rotation and impact response varying by location. These results emphasize the need for friction-specific and sport-specific testing, particularly for snowsports, where surface conditions like snow and ice can alter kinematics. Enhanced testing is critical for improving helmet design to reduce injury risk and optimize protection for snowsport athletes.

REFERENCES

Bailly, N., Afquir, S., Laporte, J.-D., Melot, A., Savary, D., Seigneuret, E., Delay, J.-B., Donnadieu, T., Masson, C., & Arnoux, P.-J. (2017). Analysis of Injury Mechanisms in Head Injuries in Skiers and Snowboarders. *Medicine and Science in Sports and Exercise*, *49*(1), 1–10. https://doi.org/10.1249/MSS.0000000000001078

Bland, M. L., Mcnally, C., & Rowson, S. (2018). Headform and neck effects on dynamic response in bicycle helmet oblique impact testing. *IRCOBI Conference Proceedings*. IRCOBI. https://api.semanticscholar.org/CorpusID:182431143

Bonugli, E., Cormier, J., Reilly, M., & Reinhart, L. (2017). *Replicating Real-World Friction of Motorcycle Helmet Impacts and Its Effects on Head Injury Metrics*. https://doi.org/10.4271/2017-01-1433

Camacho, D. L. A., Nightingale, R. W., & Myers, B. S. (1999). Surface friction in near-vertex head and neck impact increases risk of injury. *Journal of Biomechanics*, *32*(3), 293–301. https://doi.org/10.1016/S0021-9290(98)00178-X

Haider, A. H., Saleem, T., Bilaniuk, J. W., & Barraco, R. D. (2012). An Evidence Based Review: Efficacy of Safety Helmets in Reduction of Head Injuries in Recreational Skiers and Snowboarders. *The Journal of Trauma and Acute Care Surgery*, *73*(5), 1340–1347. https://doi.org/10.1097/TA.0b013e318270bbca

Keim, S., Begonia, M. T., Kieffer, E. E., & Rowson, S. (2022). *Snow Sport Helmet STAR Protocol*. http://hdl.handle.net/10919/108314

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, *82*, 1–26. https://doi.org/10.18637/jss.v082.i13

This paper is a student paper from the 19th Injury Biomechanics Symposium and is published in a special issue of SAE International Journal of Transportation Safety.
It is preliminary work, has not been peer reviewed, and should not be cited because it is a work in progress.

Levy, A. S., Hawkes, A. P., Hemminger, L. M., & Knight, S. (2002). An analysis of head injuries among skiers and snowboarders. *The Journal of Trauma*, *53*(4), 695–704. https://doi.org/10.1097/00005373-200210000-00013

Nachbauer, W., Kaps, P., Hasler, M., & Mössner, M. (2016). Friction Between Ski and Snow. In F. Braghin, F. Cheli, S. Maldifassi, S. Melzi, & E. Sabbioni (Eds.), *The Engineering Approach to Winter Sports* (pp. 17–32). Springer. https://doi.org/10.1007/978-1-4939-3020-3_2

Petersen, P. G., Smith, L. V., & Nevins, D. (2020). The effect of surface roughness on oblique bicycle helmet impact tests. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *234*(4), 320–327. https://doi.org/10.1177/1754337120917809

Rowson, S., & Duma, S. M. (2013). Brain Injury Prediction: Assessing the Combined Probability of Concussion Using Linear and Rotational Head Acceleration. *Annals of Biomedical Engineering*, *41*(5), 873–882. https://doi.org/10.1007/s10439-012-0731-0

Sances, A., Carlin, F., & Kumaresan, S. (2002). Biomechanical analysis of head-neck force in hybrid III dummy during inverted vertical drops. *Biomedical Sciences Instrumentation*, *38*, 459–464.

Stark, N., Geiman, T., Gagliardi, S., Wood, M., Viano, L., & Rowson, S. (2023). *Headform Friction Coefficients Relevant to Helmet Testing*.

Takhounts, E. G., Craig, M. J., Moorhouse, K., McFadden, J., & Hasija, V. (2013). *Development of Brain Injury Criteria (BrIC)*. 2013-22–0010. https://doi.org/10.4271/2013-22-0010

Wasden, C. C., McIntosh, S. E., Keith, D. S., & McCowan, C. (2009). An Analysis of Skiing and Snowboarding Injuries on Utah Slopes. *Journal of Trauma and Acute Care Surgery*, *67*(5), 1022. https://doi.org/10.1097/TA.0b013e3181b0d559

Weber, C. D., Horst, K., Lefering, R., Hofman, M., Dienstknecht, T., Pape, H.-C., & TraumaRegister DGU. (2016). Major trauma in winter sports: An international trauma database analysis. *European Journal of Trauma and Emergency Surgery: Official Publication of the European Trauma Society*, *42*(6), 741–747. https://doi.org/10.1007/s00068-015-0596-7