Surface Friction Implications for Snowsport Helmets

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Abstract Head injuries account for 15% of snowsport-related injuries and are the leading cause of fatalities in snowsports. Research indicates snowsport helmets could reduce head injuries by between 21% and 45%, although optimising performance through realistic testing could further reduce injuries. Notably, 65–70% of snowsport traumatic brain injuries occur against ice or snow, a low-friction surface. Therefore, this study aimed to evaluate how surface friction affects snowsport helmets' oblique impact response kinematics. We measured helmet static coefficient of friction (COF) against high-COF (80-grit sandpaper) and low-COF (steel) surfaces using a tribometer. Oblique impact testing of 10 snowsport helmet models was done at 5 m/s onto a 45-degree anvil with high-COF and low-COF surfaces. Linear mixed-effect models were used to compare the effects of location and friction surface on linear and rotational kinematics. The average COF of helmet shells against 80-grit sandpaper was 0.76 ± 0.03 and 0.27 ± 0.09 against steel. Surface friction affected linear and rotational head impact kinematics and changed how the helmets rotated off the anvil. These effects underscore the need for sport-specific lab testing. Such research is crucial for improving helmet design to minimise injury risks and optimise protection for snowsport athletes.

Keywords Friction, helmet, impact kinematics, oblique impacts, snowsport.

I. INTRODUCTION

Snowsports attract 125 million enthusiasts worldwide, with over 20 million Americans engaging in skiing or snowboarding every year [1-3]. Despite their popularity, these activities carry significant risks, including bone fractures, joint injuries, and head injuries. Head injuries represent approximately 15% of all snowsport-related injuries yet account for more than 40% of snowsport injuries treated at trauma centres [3-5]. Moreover, head injuries are the leading cause of fatalities in snowsports [2][6-7]. Previous research suggests that using helmets could prevent up to 11 fatalities per season and reduce severe head injuries by 21–45% [8-9], although optimising performance through realistic testing could further reduce injuries. Consequently, helmets have been adopted among snowsport participants in recent years [10-11].

Current snowsport helmets undergo standardised testing focused on linear impacts [12-13]. However, linear and rotational acceleration contributes to brain injury risk [14-19]. In the context of snowsports, where skiers and snowboarders frequently reach high speeds [20-21], falls often result in impacts where the velocity vector comprises both normal and tangential components relative to the ground. Thus, mitigating impact-induced rotational kinematics is essential in reducing the risk of brain injuries among snowsport athletes. In response, many manufacturers have integrated technologies to reduce rotational head kinematics during impact [22-24]. Bicycle impacts happen similarly with pre-impact normal and tangential velocities [16][25-27]. To account for this, many researchers test these helmets using an oblique drop tower with a 45° steel anvil covered in 80-grit

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sandpaper to mimic asphalt [25][28-32]. Yet, it is important to note that 65–70% of snowsport traumatic brain injuries occur when the head impacts ice or snow [20], surfaces with frictional properties considerably lower than 80-grit sandpaper commonly used in helmet testing. The COF of ice and snow at 80 N normal force against polyurethane materials ranges from 0.07 to 0.12 [43]. This discrepancy highlights a gap in current testing methodologies, underscoring the need for a better approximation of snow and ice conditions to assess helmet performance under realistic scenarios.

Surface friction has been demonstrated to influence impact kinematics across various scenarios, including simulations and replicate testing involving bicycle, motorcycle, and football helmets [33-41]. Simulation analyses have revealed that surface friction impacts head kinematics [35][41]. Furthermore, experimental bicycle helmet tests by Petersen et al. indicated that increased surface friction led to a rise in rotational kinematics and impact duration but not linear kinematics. This study also noted variations in sensitivity to friction changes depending on the impact location, with side impacts mainly affected [37]. Notably, high-friction scenarios using 80-grit sandpaper surfaces resulted in a clockwise headform rotation after impacting the anvil, while low-friction surfaces led to a counterclockwise headform rotation [37]. Bonugli et al. found similar effects on motorcycle helmets, where friction influenced rotational kinematics, altering the movement off the anvil from sliding to rotating. Finan et al. assessed the impact of surface friction on football helmets, noting that while low-friction surfaces minimally affected peak linear acceleration (PLA), they significantly altered peak rotational acceleration (PRA), in some cases increasing it and in others decreasing it. These variations highlight the importance of friction in the testing process and underscore the necessity for sport-specific evaluations. Given the differences in impact kinematics influenced by surface conditions, investigating the effects of friction on snowsport helmets becomes crucial.

This study aims to evaluate how impact surface friction affects headform response kinematics during oblique impacts when testing snowsport helmets. We hypothesised that linear and rotational kinematics will decrease under low-friction conditions compared to high-friction ones. Additionally, we expected changes in the headform rotation direction off the anvil during low-friction impacts. These findings will highlight the importance of sport-specific testing and inform the development of helmets better suited to the conditions encountered by snowsport athletes.

II. METHODS

This study comprised both friction testing and oblique impact testing. We first tested friction using a custom-built tribometer to measure the static coefficient of friction (COF) between the surfaces of two helmet models and low-friction and high-friction impact surface materials. Subsequently, we performed oblique impact tests on 10 helmet models against the high-friction and low-friction surfaces to understand how these interactions influence helmet impact response.

Friction Testing

A custom tribometer was used to measure the static COF of each helmet shell against a high-friction surface (80-grit sandpaper) and a low-friction surface (steel) using the methods described by Stark *et al.* [42]. 1.5-inch diameter coupons were cut from each helmet model (Fig. 1).

Fig. 1. The 10 helmet models used in this study.

Each helmet coupon was mounted to a fixed frame, and an 80 N load was applied to a sled with either 80-grit sandpaper or steel interacting surface (Fig. 2). 80 N normal force was chosen to match the normal force used to compare headform friction's influence on oblique impact kinematics [42]. The sled consisted of top discs that could change between sandpaper mounted on steel and a clean steel surface, a pancake loadcell to measure the applied force, and a bottom low-friction sliding surface. Once the 80 N normal force load was confirmed, a tangential force was applied to the sled. The tangential force was applied through a wire, which passed over a pulley and was connected to a bucket. Incremental weights were added to the bucket until the sled began to move, overcoming the static COF. Additionally, an in-line load cell was used to measure the force applied (Fig. 2). The static COF between the interacting surface and helmet sample was calculated using the methods in Stark *et al.* accounting for the low-friction sliding surface of the system [42]. We conducted four trials of each helmet model sample against steel and 80-grit sandpaper. A new coupon was used for each test to avoid degradation. Coupons were extracted from two helmets of the same model, ensuring they were taken from areas devoid of specific helmet features (e.g., avoiding air vents and seams).

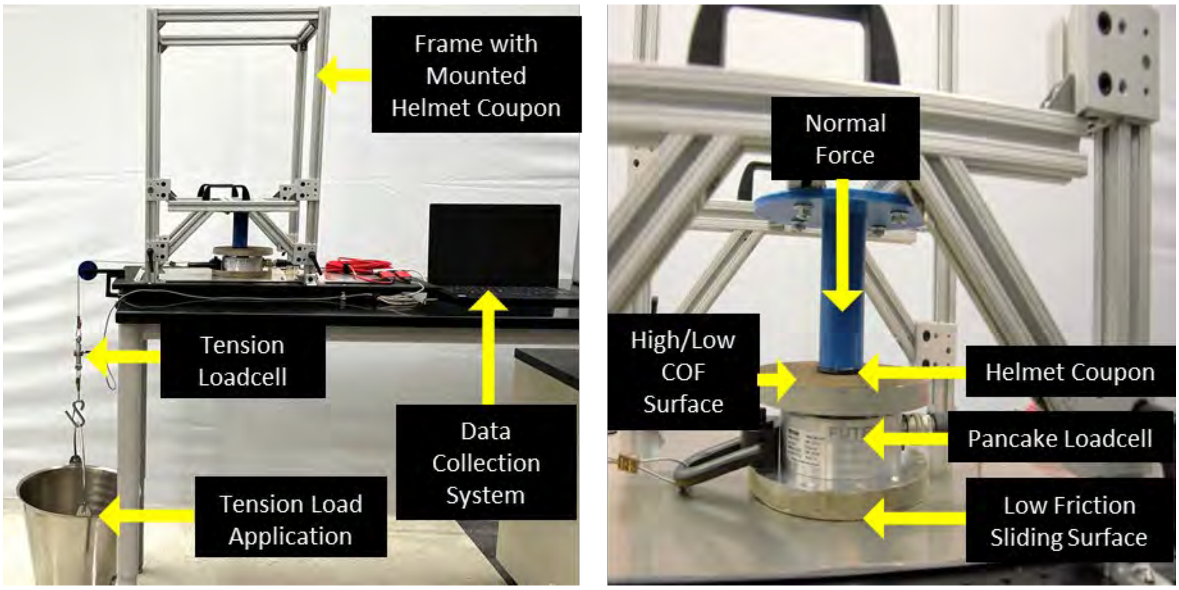

Fig. 2. Tribometer used to measure the static coefficient of friction (COF) of the helmet coupons against the low-friction (steel) and high-friction (80-grit sandpaper) surfaces.

Oblique Impact Testing

An oblique drop tower was used to conduct impact testing of 10 helmet models (Fig. 3). Impact tests were performed using a helmeted National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform onto a 45° anvil. Each helmet model was tested at three impact locations (front, side, and rear boss), two anvil friction conditions (high and low), and a drop speed of 5.0 m/s (3.5 m/s tangential, 3.5 m/s normal) (Fig. 3). Each individual helmet was impacted only once per location. The high-friction condition was when the anvil surface was covered with 80-grit sandpaper, commonly used in bicycle helmet testing to represent asphalt. COF between snow or ice and polyurethane materials ranges from 0.07 to 0.12 under an 80 N force [43]. Due to the complex nature of snow and ice, the low-friction condition was a clean steel surface of the 45° anvil, providing a COF closer to snow and ice than the sandpaper. The drop velocity was selected based on real-world head impact data and current testing standards [12-13][44]. All helmet models were tested without extraneous attachments and were fitted in accordance with manufacturer recommendations.

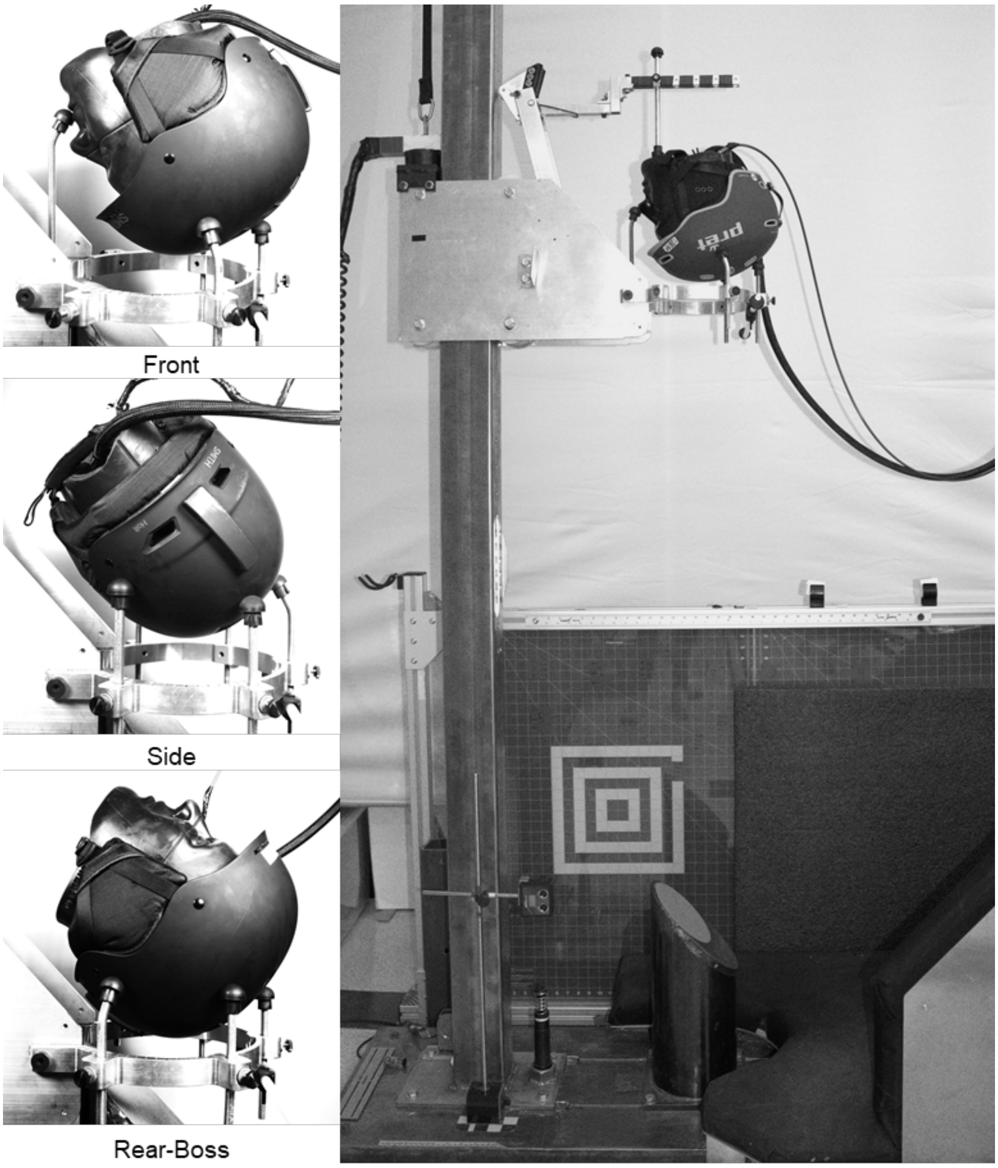

Fig. 3. Custom test rig used for snowsport helmet testing with different friction surfaces. A helmeted NOCSAE headform is dropped onto an angled anvil to generate an oblique impact. Impacts occurred at the front, side and rear-boss locations of each helmet.

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 centre of gravity (CG). Data were collected at a sampling rate of 20 kHz.

Analysis

Acceleration and ARS data were transformed using a rotation matrix to account for the offset angle of the sensor package when mounted at the NOCSAE headform CG. 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 [45]. Rotational acceleration was then computed using the five-point central difference method. Impact duration was calculated as the difference between the minimum time in which an acceleration component exceeded 5 g post-trigger and the maximum time in which an acceleration component fell below 5 g after the peak PLA was recorded.

Previous literature has found that headform spin direction off the anvil, clockwise or counterclockwise, can change with surface friction [36-37]. To account for headform spin direction after impacting the anvil, peak resultant rotational kinematic values were computed, and a sign was added to it based on analysis of the axis-specific signals to determine if any impacts resulted in rotation in the opposite direction for each test. Specifically, for side and rear-boss impacts, a positive value indicates clockwise rotation off the anvil, while a negative value signifies counterclockwise rotation. For front impacts, a positive value signifies counterclockwise rotation, and a negative value indicates clockwise rotation. We used a linear mixed-effect model ($\alpha < 0.05$, lmerTest Package [46]) to analyse how the impact location and friction surface affect PLA, PRA and peak rotational velocity (PRV) data, including their interaction. This analysis also accounts for spin direction off the anvil, while treating helmet model as a random effect (R Version 3.3.0, RStudio; Boston, Massachusetts, USA).

Although we identified headform spin direction for each impact, 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 [15][19]. Linear mixed effects (LMER) 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 [46]) to evaluate friction level effects across locations.

III. RESULTS

Friction Testing

On average, the helmet shells exhibited a COF of 0.86 ± 0.28 (mean ± standard deviation) against 80-grit sandpaper and a lower COF of 0.29 ± 0.11 against steel. Each helmet was tested against both the low-friction and high-friction surface (Table 1).

Table 1: Coefficient of friction (COF) of each helmet against high-friction surface (80-grit sandpaper) and low-friction surface (steel) measured with the tribometer. (mean ± standard deviation)

Helmet Model	COF 80-Grit Sandpaper	COF Steel
Giro Ledge MIPS	0.84 ± 0.11	0.35 ± 0.05
Lucky Bums	0.72 ± 0.03	0.20 ± 0.04
Giro Nine MIPS	0.82 ± 0.08	0.37 ± 0.03
Giro Seam	0.92 ± 0.03	0.45 ± 0.10
Oakley MOD5	0.94 ± 0.04	0.25 ± 0.02
POC Receptor Bug	0.97 ± 0.09	0.25 ± 0.01
Pret Cynic MIPS	0.87 ± 0.05	0.30 ± 0.06
Smith Holt	0.90 ± 0.04	0.22 ± 0.05
Switcher MIPS	0.95 ± 0.02	0.38 ± 0.09
Wildhorn Drift	0.83 ± 0.06	0.26 ± 0.02

Oblique Impacts

Across location and helmet models, there was a main effect of friction on PLA, where PLA decreased an average of 26 g's with a decrease in surface friction (95% confidence interval (CI): [-32, -19] g; $p < 0.0001$) (Fig. 2). Specifically, the PLA decreased by 19 g for front impacts, 29 g for side impacts, and 30 g for rear-boss impacts for low-friction impacts compared to high-friction impacts. Additionally, it was observed that the impact duration across all locations was, on average, 0.58 ms shorter in low-friction conditions compared to high-friction impacts ([-1.25, 0.08] ms; $p = 0.091$) (Fig. 4).

The linear mixed models that maintained rotation directionally showed that PRA ($p < 0.0001$) and PRV ($p < 0.0001$) responses varied with friction and impact location (Fig. 4). A post hoc least squares means analysis was conducted to evaluate the interaction effect. At the front location, low-friction impacts, on average, were associated with a PRA increase of 1650 rad/s^2 ([-492, 3792] rad/s^2; $p = 0.134$) and a PRV increase of 7 rad/s ([0, 15] rad/s; $p = 0.058$) compared the high-friction impacts. The side and rear-boss impacts were more sensitive to the impact surface COF (Fig. 4). For side impacts, reduced surface friction on average led to a PRA decrease of 6067 rad/s^2 ([-3924, -8209] rad/s^2; $p < 0.0001$) and PRV decrease of 23 rad/s (-15, -31 rad/s; $p < 0.0001$). However, at the rear-boss location, a low-friction surface, on average, led to a PRA decrease of 8965 rad/s^2 ([-11107, -6822] rad/s^2; $p < 0.0001$) and PRV decrease of 35 rad/s (-43, -27 rad/s; $p < 0.0001$). These large differences in PRA were due to the headform rotating off the anvil in different directions based on the surface friction condition.

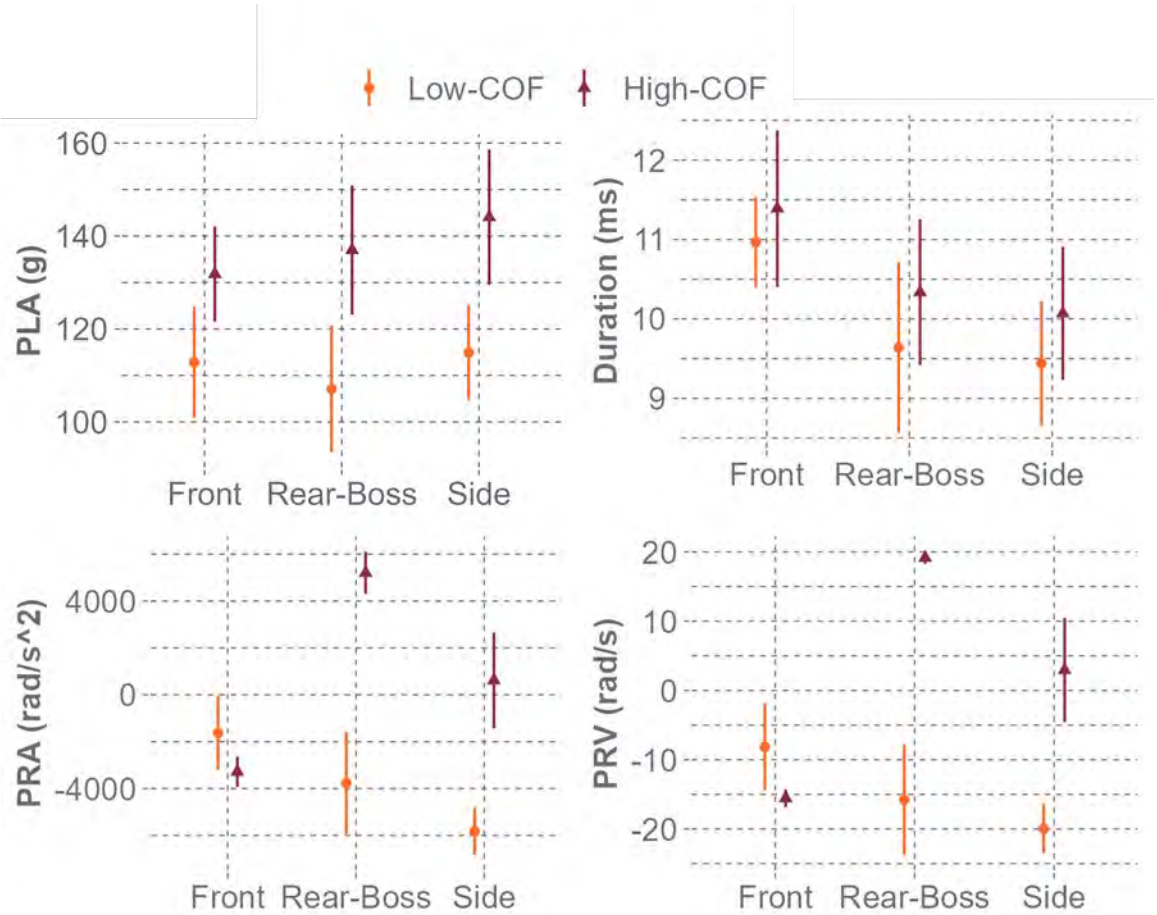

Fig. 4. Directional maintained comparison of duration, peak resultant linear acceleration (PLA), peak resultant rotational acceleration (PRA), and peak resultant rotation velocity (PRV) for high-friction (High-COF), 80-grit sandpaper, and low-friction (Low-COF) steel. Mean and 95% confidence intervals are displayed.

Observations on headform spin direction further underscored the influence of model and impact location on helmet behaviour. In high-friction conditions, side impacts resulted in seven helmets bouncing off the anvil clockwise (CW) and three rolling off counterclockwise (CCW). Conversely, the low-friction side impacts all helmet models rolled off anvil CCW (Fig. 5). At the rear-boss location, high-friction conditions consistently caused helmets to bounce off CW, whereas in low-friction, all but one model rolled off CCW. The one helmet that bounced off the anvil at the high- and low-friction conditions was the Oakley MOD5, which has a distinctive side/back panel. For front high-friction impacts, all helmet models bounced CW off the anvil, and for the low-friction impacts, all but two helmet models also bounced CW off the anvil. The two models that did not were the Wildhorn Drift and the Giro Ledge MIPS; these rolled off the anvil CCW instead.

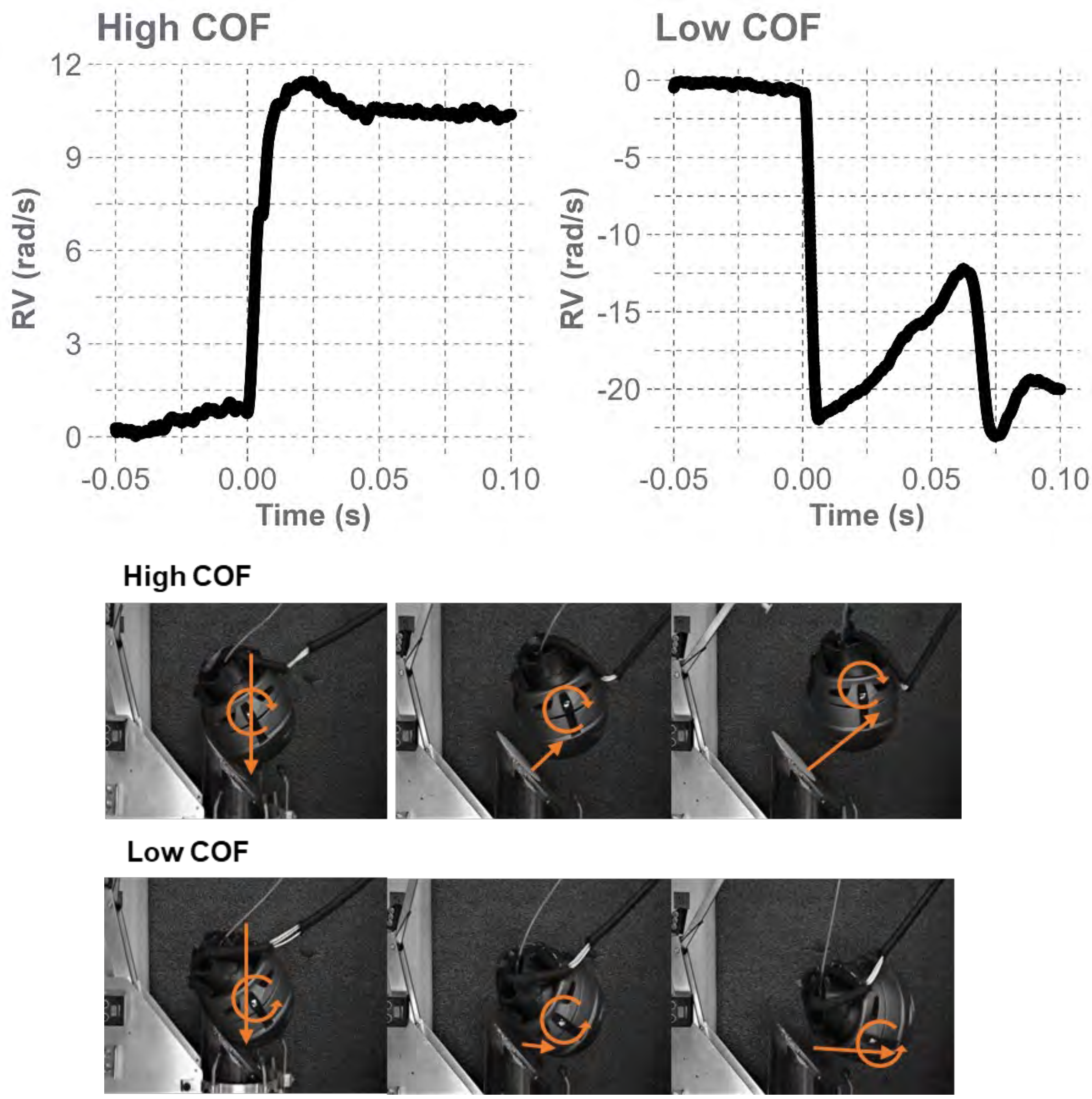

Fig. 5. Representative impact sequence for the High-COF surface (80-grit sandpaper), where the helmet bounces off the anvil spinning clockwise (CW), and the Low-COF surface (steel), where the helmet rolls off the anvil spinning counterclockwise (CCW).

The impact of location and surface friction on magnitude non-directional data was distinct from the effects on directional data, clockwise or counterclockwise (Fig. 5). For front impacts, the low-friction condition decreased the magnitude of PLA by 26 g ([-32, -19] g; $p < 0.0001$), PRA by 548 rad/s^2 ([-1702, 606] rad/s^2; $p = 0.357$), and PRV by 3.5 rad/s ([-6.9, -0.1] rad/s; $p = 0.047$). The rear-boss location had similar magnitude of rotational kinematics regardless of friction condition, with a mean difference of only -303 rad/s^2 PRA ([-1457, 851] rad/s^2; $p = 0.609$) and only 0.6 rad/s PRV ([-2.8, 3.9] rad/s; $p = 0.750$) (Fig. 6). However, there was a mean reduction of 30 g PLA ([-41, -18] g) with low-friction impacts ($p < 0.0001$). Conversely, for side impacts, PRA increased by an average 2983 rad/s^2 ([1828, 4137] rad/s^2; $p < 0.0001$) for low-friction impacts compared to high-friction impacts, and PRV increased by an average 9.0 rad/s ([5.6, 12.4] rad/s; $p < 0.0001$). These increases show that the low-friction side impacts were more severe compared to high-friction side impacts. Although rotational kinematics increased at the side impact location for low-friction conditions, PLA decreased by -29 g ([-41, -18] g; p < 0.0001).

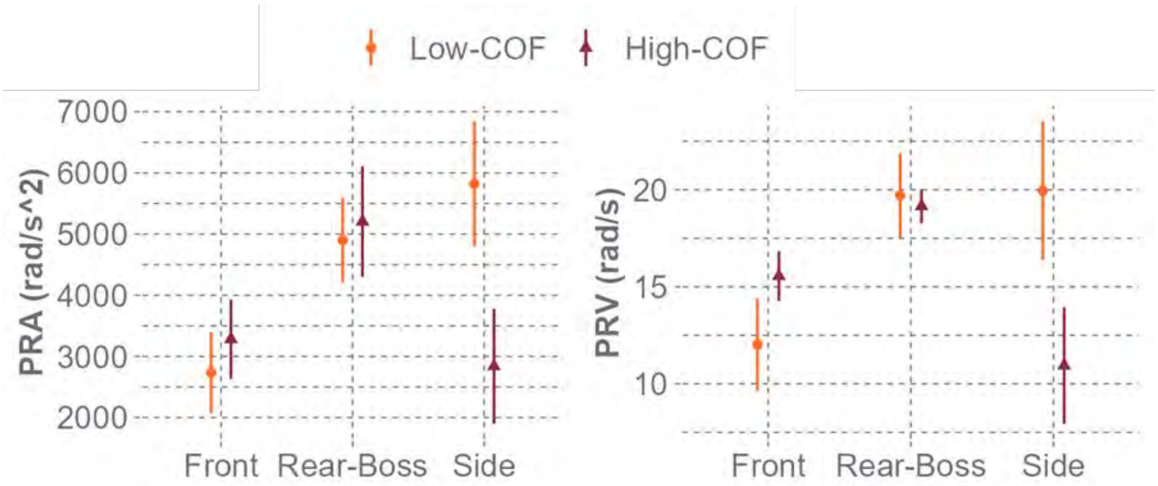

Fig. 6. Magnitude comparison of peak resultant rotational acceleration (PRA) and peak resultant rotation velocity (PRV) by impact location for high friction (High-COF), 80-grit sandpaper, and low-friction (Low-COF) steel.

IV. DISCUSSION

Research across various helmet types, including bicycle, motorcycle, and football helmets, has highlighted the role of surface properties in influencing impact kinematics. Unlike these impacts, 65–70% of snowsport TBIs occur against ice or snow, which have inherently lower friction than typical surfaces encountered in other sports. In this study, we measured the COF of helmets against steel and 80-grit sandpaper and evaluated the effect of friction on oblique snowsport helmet impacts. We found a large effect of anvil friction on PLA, PRA, and PRV impact responses, amplified by variations in post-impact rotation off the anvil and dependent on impact location. Interestingly, when comparing high- and low-friction conditions, the magnitudes of PRV and PRA were similar for impacts to the rear-boss and front of the helmet. However, side impacts were distinguished by significantly higher PRA and PRV in low-friction scenarios.

Across all impact locations, PLA against 80-grit sandpaper was, on average, 20% (16–24%) greater than against the low-friction steel surface. The low-friction condition reduced PLA because the helmets slid off the anvil, causing a lower linear velocity change compared to the high-friction condition where the helmets bounced off the anvil. This observation aligns with existing studies on the impact of surface friction on motorcycle and football helmets during oblique drops [33][36]. Finan *et al.* reported a less pronounced reduction in PLA, which may be attributed to the relatively minor differences in COF across their test conditions [36]. In contrast, Petersen *et al.* did not observe a reduction in PLA with decreased friction, potentially due to their study's inclusion of a neck component [37]. The presence of the neck can influence PLA outcomes by altering the effective mass and moment of inertia (MOI), and inducing axial loading to the neck during impact, which the Hybrid III is not validated for [24][37][47][48].

The impact of friction on rotational kinematics was multifaceted, with a notable variation in friction effect on rotational kinematics based on impact location. For the side and rear-boss impacts, when directionality in the signal was maintained, PRV and PRA values were positive on average for high-friction impacts, suggesting that the majority of helmet models bounced off the anvil CW. Conversely, for low-friction impacts on steel, PRV and PRA values were, on average, negative; thus, the majority of helmet models skidded off the anvil CCW, rather than bouncing. However, at the side impact location, three helmet models exhibited negative PRV and PRA for both high- and low-friction conditions. These models included the Giro Seam, Giro Nine MIPS, and the Switcher MIPS, which all have ridges along the side of the helmet. At the rear-boss impact location, the Oakley MOD5, which has a distinctive side/back panel, consistently showed positive PRA and PRV in both friction scenarios. The divergent behavior of these models may be attributed to their helmet geometries or the effective MOI.

Contrary to the observed trends in rotational direction for side and rear-boss impacts, the front impact location did not exhibit the same average change in rotational direction between high- and low-friction conditions. All helmet models, except for the Wildhorn Drift and the Giro Ledge MIPS models, bounced off the anvil under both high- and low-friction scenarios. The Giro Ledge MIPS model, characterised by its lack of a brim and a flatter front, and the Wildhorn Drift model, which has a small brim that showed significant indentation after impact, rotated CCW, skidding off the anvil during low-friction impacts. The majority of tested helmet models featured a front brim, and this design aspect may have interacted with the anvil, causing the helmets to bounce off rather than skid. Despite the absence of a directional change in PRV and PRA response at the front impact location, there was still a meaningful reduction in rotational kinematics for low-friction impacts, with PRV decreasing by an average of 48% and PRA decreasing by an average of 50%. The results indicated that reducing impact surface friction causes alterations in rotational kinematics regardless of impact location, but the geometry of helmets also has a role in the impact response. These variations might not impact injury prediction models that focus solely on peak resultant values, but they could be crucial for models that take direction into account.

The observed differences in post-impact rotation, particularly for rear-boss and side impacts, are largely attributable to how friction levels affect the helmet's rotation off the anvil. The PRV and PRA magnitude for front and rear-boss impacts were comparable between high- and low-friction impacts. Therefore, the large changes in PRV and PRA at the rear-boss location were primarily due to the difference in how the head rotates off the anvil. However, for side impacts, low-friction impacts resulted in an average increase of 82% (69–106%) in PRV and 105% (81–153%) in PRA when compared to high-friction impacts. This trend aligns with findings from Petersen *et al.*, who also reported a significant increase in PRA magnitude with low-friction surfaces for side impacts [37]. These results indicate that concussion risk would be underpredicted during side impact testing when a high-friction surface is used, but low-friction impacts occur in real-world impacts. Though front and rear-boss impact locations, there would be similar conclusions on concussion risk between high- and low-friction conditions. These findings emphasise the importance of accurately representing frictional interactions in helmet testing procedures. Matching real-world friction should be considered best practice for evaluating concussion risk in representative impacts.

It is important to note that the impacts in Petersen et al.'s study involved a Hybrid III neck. Bland et al. evaluated the influence of anthropomorphic test device headforms with and without a Hybrid III neck against a high-friction surface. Their results showed that the presence of a neck increased the duration and decreased the PRV and PRA across impact location across impact locations, although the rotation off the anvil was not evaluated. We suspect a similar response change if a neck were included in these impacts, though there could be unforeseen changes based on rotation off the anvil for low-friction impacts. The addition of a neck could restrain the rotational components of the impact, altering the impact response [47][49]. Moreover, the addition of a neck would alter the MOI and CG of the headform, which has been shown to have a large effect on oblique impact kinematics [47][50].

Our findings indicated that the average COF of helmet shells against steel and 80-grit sandpaper is consistent with previous research, which reported steel COF values ranging from 0.2 to 0.6 and 80-grit sandpaper to be 0.61 $\pm$ 0.01 [33][37]. 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 under an 80 N force [43]. This is lower than the COF values we observed between helmet shells and steel, suggesting that the reduction in PLA, PRA, and PRV could be more pronounced on actual snow or ice. However, replicating snow and ice conditions for consistent laboratory testing poses unique challenges. Furthermore, the potential for snow to indent upon impact, altering impact kinematics, cannot be overlooked [20][51]. For instance, Bailly *et al.* and Dressler *et al.* reported indentation from helmeted impacts into snow during field testing [20][51]. This deviation in frictional properties and the additional variable of snow indentation highlight the complexities of accurately simulating real-world snowsport impacts in a laboratory setting and emphasise the importance of considering these factors in helmet design and testing.

This study was limited in the helmet samples tested and testing conditions. With only 10 helmet models evaluated, the findings may not fully represent the diverse performance characteristics of all snowsport helmets. Additionally, the testing only included three impact locations and one speed (5 m/s), although snowsport athletes are likely travelling over a broader range of speeds. Furthermore, the interaction between the headform and the helmet's interior, a critical factor in the frictional response to oblique impacts, was not examined. Future work should include testing additional helmet models over an extensive range of velocities with real snow and ice to be more representative of real-world snowsport head impacts.

V. CONCLUSION

Our findings reveal that friction influences PLA, PRA and PRV in helmet impacts, with the extent of impact and post-impact rotation directionality varying by location. We also determined that friction alters rotational kinematics regardless of impact location, but the geometry of helmets also plays a role in the impact response. These variations highlight the importance of friction in the testing process and underscore the necessity for sport-specific evaluations. Given the differences in impact kinematics influenced by surface conditions such as snow and ice, there is a need for snowsport-specific testing to enhance safety and performance. Such research is crucial for improving helmet design to minimise injury risks and optimise protection for snowsport athletes. This study's limitations were that it tested a small sample of helmet types at a single speed, using steel for the low-friction surface. Therefore, future work should include testing more helmet models across various impact speeds and comparing the ice and snow COF to the steel anvil.

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