Laboratory Evaluation of Mountain Bike Helmet Impact Performance against a Surrogate Compliant Mountain Biking Trail Surface versus a Conventional Surrogate Road Surface

Megan L. Bland-Rothgeb, Alec Redmann, Tony White

Abstract Although research suggests that mountain biking (MTB) crashes often involve falls onto compliant trail surfaces, MTB helmets are presently designed around rigid surface impact tests. This study describes the investigation of a laboratory method for evaluating MTB helmets in oblique impacts against a surrogate compliant MTB trail surface. A headform was subjected to drop tests onto compliant surfaces at local MTB trails. Matched tests were repeated in a laboratory setting to identify a surrogate surface that could replicate the impact response of the trail surfaces. A conventional MTB helmet was then subjected to oblique impact testing against the surrogate trail surface as well as a rigid surrogate road surface typically used in helmet testing. Generally, the surrogate trail surface produced decreased linear and rotational kinematics and longer durations compared to the surrogate road surface. However, these trends were dependent upon impact location, with higher peak rotational velocities observed for the trail surface at one location. Notably, predicted brain injury risks (Brain Injury Criteria, Abbreviated Injury Scale 2) were moderate (22-36%) across both surfaces. Researchers and manufacturers can use similar testing against compliant surfaces to evaluate previously unexplored aspects of MTB helmet impact performance.

Keywords Biomechanics, brain injury, cycling, head protection, oblique impact.

I. INTRODUCTION

Mountain biking (MTB) has steadily gained popularity since its introduction in the 1970s [1]. In recent years, over 8.5 million Americans were estimated to have engaged in MTB annually [2]. While MTB is a good source of exercise, adventure, and competition, it also involves inherent injury risks. Injury rate estimates range from 4-40 injuries per 1,000 hours of riding, depending on the type and intensity of riding [1][3-4]. The head is one of the most frequently injured body regions in MTB [3-7]. Concussion, a form of mild traumatic brain injury (TBI), is a common injury diagnosis, accounting for 3-19% of all injuries [1][3-4][6][8-10]. More severe TBIs are fortunately reported to be less common [8]. Although multiple studies have shown that bicycle helmets are generally effective in reducing risk of head injury during cycling accidents [11-14], these studies have primarily focused on cyclists in urban areas and on road-specific crash conditions. The protective effect of MTB helmets in other MTB-specific impact scenarios has not been thoroughly investigated.

MTB helmets are presently subject to the same regulatory standards as road helmets. To be sold in the U.S., helmets must pass the Consumer Product Safety Commission (CPSC) 16 CFR Part 1203 standard [15]. The impact attenuation portion of this standard dictates that helmets be subjected to vertical drop tests onto flat, hemispherical, and kerbstone anvils. All anvils are comprised of solid steel. Resulting impact forces are normal to the anvil surface (thus termed *normal* impacts), and helmets must limit the linear acceleration of the head to below 300 g. The European helmet standard, European Norm (EN) 1078, imposes similar test requirements [16]. The only MTB-specific helmet standard at present is the voluntary American Society for Testing and Materials (ASTM) F1952 standard, which is intended for downhill MTB racing helmets [17]. The drop tests in this standard are markedly similar to those in the CPSC standard, with the primary differences being higher impact speeds for hemispherical and kerbstone testing and a slightly modified helmet coverage requirement.

While current standards evaluate the ability of bicycle helmets to manage normal impact forces and head linear accelerations, research investigating cycling accidents indicates that cyclists' heads typically impact a surface at an oblique angle during a crash, generating both normal and tangential reaction forces [18-21]. The

M. L. Bland-Rothgeb, PhD, (megan_bland@trekbikes.com, +1 920-478-2191), Helmet Research Engineer, A. Redmann, PhD, Helmet Research Engineer, and T. White, Engineering Manager, all worked at Trek Bicycle Corporation in Wisconsin, USA, at the time of the study.

addition of tangential forces may give rise to considerable rotational kinematics of the head, which prior research has implicated as a key mechanism of diffuse brain injuries like concussion [22-24]. Given this clinical relevance, helmet technologies intended to reduce rotational head impact kinematics have been created and laboratory oblique impact test methods have been developed for the purposes of helmet evaluation [25-29]. One example is the Virginia Tech Summation of Tests for the Analysis of Risk (VT STAR) protocol, which rates bicycle helmets based on their ability to minimise linear and rotational kinematics of the head during oblique impacts [27]. The STAR protocol creates the normal and tangential reaction forces involved in oblique impacts by dropping a helmeted headform onto an angled anvil. The anvil, which is constructed of steel and coated with 80-grit sandpaper per motorcycle helmet standards [30], functions as a surrogate road surface.

Research on MTB accidents indicates that falls onto compliant trail surfaces are among the most frequent crash scenarios resulting in injury [3][5][8]. This is in contrast to the rigid anvils used in standards and oblique impact testing, which are more reflective of a rigid road environment and may be overly stiff compared to compliant MTB trail surfaces [28]. Compliant surfaces deform and absorb energy during impact, creating a distinct dynamic profile in which the magnitude of the impact force is reduced and the duration is extended [31]. [31-32] investigated head impact response against compliant ground surfaces in equestrian sports and indeed found that head accelerations were lower in magnitude and sustained over longer durations compared to impacts against a rigid surface. The authors cautioned that the longer durations over which the lower accelerations were sustained could still result in high stresses and strains within the brain that could lead to injury [31]. In addition to differences in compliance across road and MTB surfaces, the friction of dirt or grass surfaces, which are typical around MTB trails, is generally lower than that of road surfaces [33]. This difference could have implications for the rotational energy management of helmets during oblique impacts.

Although current standards and oblique impact studies ensure that MTB helmets are evaluated in rigid, high-friction conditions similar to a road environment, evaluation of MTB helmets under compliant trail surface conditions common in MTB may provide additional insights into helmet performance. The objectives of this study were therefore to 1) develop a method for in-laboratory oblique impact testing against a surrogate compliant MTB trail surface (termed *surrogate trail surface*), and to 2) use this method to compare how the oblique impact performance of a conventional MTB helmet differs between surrogate trail and typical surrogate road surfaces.

II. METHODS

Several testing phases were conducted in the present study. The first phase consisted of impact testing at local MTB trails, the second phase consisted of matched laboratory impact testing to identify a suitable surrogate trail surface, and the third phase used results of the first two phases to inform laboratory oblique impact testing of MTB helmets against surrogate trail and surrogate road surfaces. Each section is detailed below. In general, the impact conditions described herein were selected to mirror a subset of the VT STAR impact test conditions [27]. This was done so that future test results stemming from the proposed surrogate trail surface testing could be compared to the surrogate road surface test results stemming from official VT STAR results for a given helmet.

Phase I: MTB Trail Surface Testing

Impact testing was conducted at local MTB trails in southern Wisconsin, U.S., on a clear day in early July (Fig. 1). It had not rained for several days, and the ground was firm and dry. The National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform of the VT STAR protocol [27] was dropped onto dirt and grass surfaces at flat and approximately 45-degree angled locations (confirmed using a digital level). The flat and angled drop tests reflect normal and oblique impact tests used in laboratory testing, respectively. Normal forces highlight compression properties of a compliant surface, which are related to resulting linear head kinematics, while tangential forces highlight friction and shear properties, which are related to resulting rotational head kinematics. Normal impacts involve only normal forces, while oblique impacts are more complex, involving tangential forces in addition to normal. Normal impacts were therefore conducted to provide a simpler, lower variance characterization of compliant trail surfaces before progressing to higher complexity oblique impacts.

For both normal and oblique impacts, the drop height was based on the theoretical height required to attain an impact speed of 4.8 m/s under the force of gravity. This impact speed was selected because it is used in the VT STAR protocol and is the more heavily weighted speed in the STAR calculation, reflecting the reportedly high frequency at which this impact speed is experienced in real-world cycling accidents [27]. This impact speed also produces concussion-level impact results in VT STAR testing – a relevant injury for MTB. To conduct the drops, a tester suspended the headform by a light-weight aluminum I-bolt attached to the bottom of the headform such that the superior aspect of the headform was directed towards the ground (Fig. 1). The tester lifted the headform to the predefined drop height and released the I-bolt to initiate the test. For normal impacts, the impact location was the superior aspect of the head. For oblique impacts, the impact location was shifted slightly posterior. Tests were conducted directly onto or immediately adjacent to the trails. Three trials were conducted for the dirt and grass surfaces at both the flat and angled locations, although the precise impact location was varied by several inches for each impact to avoid potential compaction due to prior impacts.

Fig. 1. A) Local MTB trails used for impact testing, B) Drop test setup for a normal impact onto a dirt surface, and C) Drop test setup for an oblique impact onto a 45-degree grass surface.

For all testing in the present study, the headform was instrumented with three linear accelerometers (Endevco 7264B-2000, PCB Electronics, Depew, NY, USA) and a tri-axis angular rate sensor (ARS3 PRO-18K, DTS, Seal Beach, CA, USA) located at the centre of gravity (CG). Data were collected at 20 kHz (SLICE MICRO, DTS, Seal Beach, CA, USA). Raw data were transformed to match the Society of Automotive Engineers Recommended Practice J211 (SAE J211) coordinate system [34]. Linear acceleration data were filtered according to SAE J211 using a channel frequency class (CFC) of 1,000, while rotational velocity data were filtered at a CFC of 175 [27][35-36]. Rotational velocity data were then differentiated using the MATLAB (MathWorks, Natick, MA, USA) two-point *diff* function to produce rotational acceleration data. Resultant peak linear acceleration (PLA), peak rotational velocity (PRV), and peak rotational acceleration (PRA) were determined per test, as well as impact duration. Impact duration was calculated as the time from when the first directional linear acceleration curve exceeded 5 g to the time when the final directional linear acceleration curve first returned below 5 g after the peak.

Phase II: Laboratory Validation of a Surrogate Trail Surface

The same testing approach that was employed for the MTB trail surface testing was replicated in-laboratory for validation of a surrogate trail surface (Fig. 2). Specifically, all drop tests were conducted at a nominal impact speed of 4.8 m/s, the impact location was the superior aspect of the NOCSAE headform for normal impact tests and slightly posterior for oblique impact tests, and three trials were conducted per impact condition.

For normal impact tests, a variety of vinyl nitrile (VN) foams (DER-TEX Corp., Saco, ME, USA) topped with synthetic grass turf (Lulind, Nickel Goods Inc., China) were evaluated, as these materials were found to represent ground surfaces in equestrian sports by [31-32]. [31] showed that VN602 and VN704 (covered with synthetic turf) were able to replicate the normal impact response of medium-to-firm ground stiffnesses, while [32] showed that oblique testing on these surfaces produced rotational results in line with concussive injury cases from equestrian accidents. VN602 and VN704 were therefore used in the present study. Additionally, VN600 and VN1000 were tested to increase the range of foam stiffnesses. All foams were 55 mm thick. One test was conducted against the concrete floor of the laboratory to provide a reference point for rigid impacts more akin to a road surface. Only one test was conducted to limit the risk of damaging test equipment. For each foam/turf surface, duration and PLA were compared to the range of normal impact MTB trail surface results using unequal variance t-tests (α=0.05) to assess the ability of the foams to reflect the response of MTB trail surfaces under normal impact forces. The two foams with results closest to the average normal impact MTB trail surface results were then used in oblique impact testing to investigate their response under the addition of tangential forces.

For oblique testing, impacts against a 45-degree anvil were conducted using a monorail drop tower that reflected the VT STAR test setup [27] (Fig. 2). Prior to each impact, the headform was positioned upside-down in the drop carriage ring to match the impact location from the oblique MTB trail surface testing. An elastic strap was used to prevent rotation of the headform during the drop. An electromagnet held the strap in place, turning off just prior to impact and releasing the strap. Upon impact, the head contacted the anvil while the carriage ring passed around the outside of the anvil. A rigid flag attached to the drop carriage passed through a photogate (BeeSpi V, NaRiKa Corp., Tokyo, Japan) just prior to head impact to measure the impact speed.

For each of the two foams that most closely replicated the normal MTB trail surface test results, a sample was cut to match the shape of the 45-degree steel anvil (Fig. 2). The foams were secured to the anvil using double-sided duct tape. Turf was added to the foam using double-sided duct tape as well as staples at the perimeter. Approximately 5 minutes were allowed to elapse between repeated impacts to each foam/turf surface. After each impact, the foam and turf were visually inspected for any residual compression or degradation, and the turf was roughly combed to prevent compaction over time. High-speed video (Chronos 1.4, Kron Technologies, British Columbia, Canada) was collected at 1,000 frames/s for each impact to look for slippage at the turf/foam and foam/steel interfaces due to inadequate fixation. The video was also used to verify that the head contacted the anvil at the intended location, i.e., that it had not rotated prior to impact. A single drop test on a surrogate road surface (80-grit sandpaper adhered to the 45-degree steel anvil [27][30]) was conducted for comparison. Only one test was conducted in this condition to limit the risk of damage to the test equipment. For each foam/turf surface, PRV and PRA were compared to the range of oblique MTB trail surface results using unequal variance t-tests (α=0.05) to assess the ability of the foam/turf samples to reflect the MTB trail surfaces under the addition of tangential forces. Duration and PLA were also checked against the oblique MTB trail surface test results to ensure that the foam/turf surfaces reflected the same trends that were found in the normal impact testing.

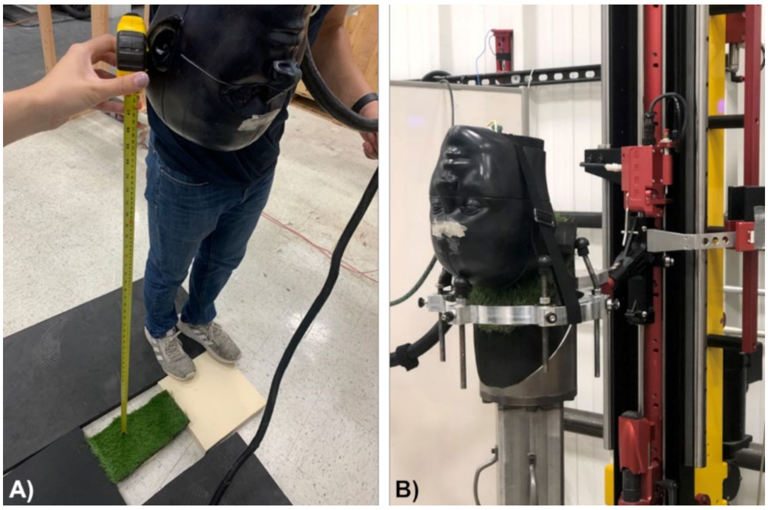

Fig. 2. A) Laboratory drop test setup for a normal impact onto a foam/turf surface, B) Laboratory oblique impact test rig with the VN1000/turf surface adhered to the 45-degree anvil.

The foam/turf surface that best represented the average oblique MTB trail surface results was designated as the validated surrogate trail surface for further helmet testing. The same foam was then subjected to repeated normal and oblique laboratory headform validation tests with the turf removed to investigate the influence of the turf on resulting kinematics. Student's t-tests were used for all comparisons (α=0.05).

Phase III: Laboratory Oblique Impact Testing of an MTB Helmet Against Surrogate Trail and Road Surfaces

A laboratory oblique impact test method for evaluation of MTB helmets against a surrogate trail surface was established using the surrogate trail surface selected from the headform validation testing in Phases I and II. Oblique impacts were conducted at 4.8 m/s using the same monorail impact setup previously described (Fig. 2). Two impact locations from the VT STAR protocol were selected for helmet testing based on a review of publicly available MTB crash videos and MTB helmets damaged in real-world crashes. One hundred and two videos of MTB crashes with a clear view of the rider's head impact were identified from Pinkbike's Friday Fails crash videos

[37]. The videos were reviewed frame-by-frame around the moment of head impact, allowing an approximate region of the initial contact point on the helmet to be recorded. In addition, 27 damaged MTB helmets returned to Trek Bicycle Corporation through a crash replacement programme were visually inspected for signs of impact, including scrapes on the shell or crushing/cracking of the foam liner. Across both methods, the majority of impacts were concentrated at the front and sides of the helmets. These impact locations are consistent with published studies investigating MTB crashes, which indicate that riders frequently fall forward over the handlebars or to the side during a crash [3][6-7]. Therefore, a front and side impact location from the VT STAR protocol (locations 2 and 5, respectively) were used for testing [27].

A conventional MTB helmet representing the general shape and construction of current MTB helmets on the market was selected for testing. The helmet was comprised of an energy-absorbing expanded polystyrene liner in-moulded into a polycarbonate shell. It also contained a visor, retention straps, a dial fit system, and comfort padding. It did not contain additional technologies specifically designed to minimise rotational impact kinematics. Consistent with the VT STAR protocol, the visor was removed prior to testing, then the helmet was fitted to the NOCSAE headform according to typical manufacturer recommendations. The helmeted headform was positioned to impact the VT STAR locations by matching angles from an inertial measurement unit (LPMS-B2, LP-Research, Tokyo, Japan) and angles inscribed on the carriage ring to those specified by the STAR protocol [27]. Each helmet sample was impacted once per impact location. Helmets were tested against one of two surfaces: the surrogate trail surface or the surrogate road surface. Three trials were conducted per impact condition.

High-speed video was taken at 1,000 frames/s of each impact to verify impact location consistency and to ensure that neither the turf nor the foam slipped during impact due to inadequate fixation. After each surrogate trail surface impact, the foam and turf were visually inspected for signs of degradation or residual compression, and the turf was roughly combed to prevent compaction over time. Additionally, before and after the helmet test series, the bare headform was dropped onto the surrogate trail surface three times. This allowed investigation of whether the surrogate trail surface changed in response to repeated impacts over the course of the study.

For all tests, the raw data were processed in the same manner as with the headform validation tests, and average kinematic metrics (duration, PLA, PRV, and PRA) were determined per impact condition. In addition, Brain Injury Criteria (BrIC) was calculated and used to determine the probability of Abbreviated Injury Scale 2 (P(AIS2)) concussive brain injury for each impact [38]. Equations 1-2 show the respective calculations for BrIC and P(AIS2), where $\omega_{x/y/z}$ are the PRVs in the x-, y-, or z-directions, and $\omega_{xC/yC/zC}$ are critical PRVs reflecting 50% probability of AIS4 (severe) brain injury. More information on BrIC can be found in [38].

$$BrIC = \sqrt{\left(\frac{\omega_x}{\omega_{xC}}\right)^2 + \left(\frac{\omega_y}{\omega_{yC}}\right)^2 + \left(\frac{\omega_z}{\omega_{zC}}\right)^2}, \quad (1)$$

$$P(AIS2) = 1 - e^{-\left(\frac{BrIC}{0.602}\right)^{2.84}}, \quad (2)$$

Variance in kinematic results was investigated by determining the coefficient of variation (CV) across the three trials per impact condition. Average CVs were compared across the surrogate trail and surrogate road surfaces. In order to lend additional insights into the effect of repeated impacts to the surrogate trail surface over time, correlation analysis was used to determine whether there was a significant relationship ($\alpha=0.05$) between trial number and kinematic results. Lastly, the influence of the impact surface and location on peak kinematics and P(AIS2) were investigated using two-way ANOVA with Tukey's HSD post hoc tests.

III. RESULTS

The normal impact MTB trail surface tests produced average durations of 5.4-8.2 ms and PLAs of 145-223 g across the grass and dirt surfaces (Fig. 3). In the matched laboratory normal impact testing (Fig. 3), VN1000/turf results did not differ significantly from the range of MTB trail surface results (duration: p=0.94, PLA: p=0.78), with duration and PLA averages that differed by only 1-3% from the average MTB trail surface results. All other tested VN foams produced significantly lower PLAs and longer durations than the MTB trail surfaces (p<0.03). After VN1000/turf, VN704/turf results were closest to the MTB trail surface results, with an average duration that was 42% longer (p<0.01) and an average PLA that was 33% lower (p=0.02) than the average MTB trail surface results. VN704/turf results were closer to the grass surface results, albeit still significantly different (17% longer duration, p=0.03; 14% lower PLA, p=0.01). Of note, the single rigid, concrete impact produced a duration and PLA that were 50% shorter and 179% greater than the average MTB trail surface results, respectively.

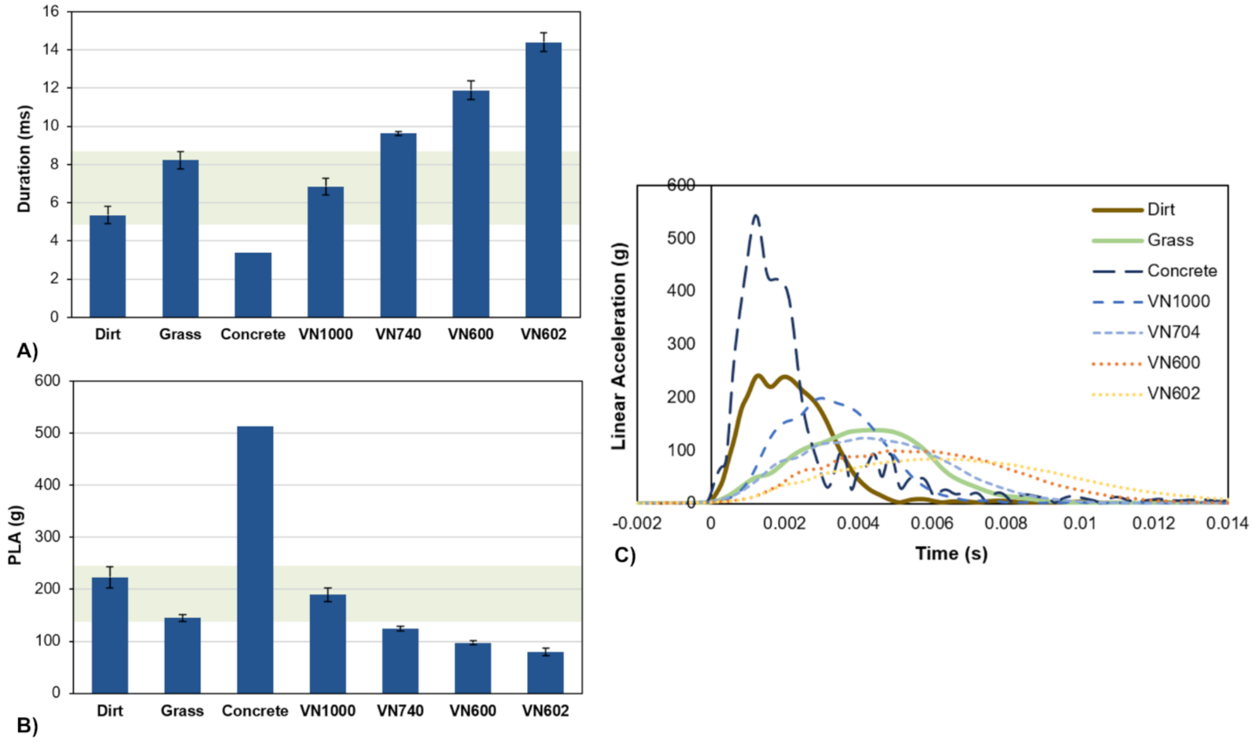

Fig. 3. Normal impact validation test results. The Dirt and Grass results are from the MTB trail surface testing, while other results are from the matched laboratory testing. All VN foams were tested with turf on the surface. A) and B) show duration and PLA results, respectively, with the green shaded regions depicting the MTB trail surface range, and C) shows example linear acceleration data over time for all surfaces.

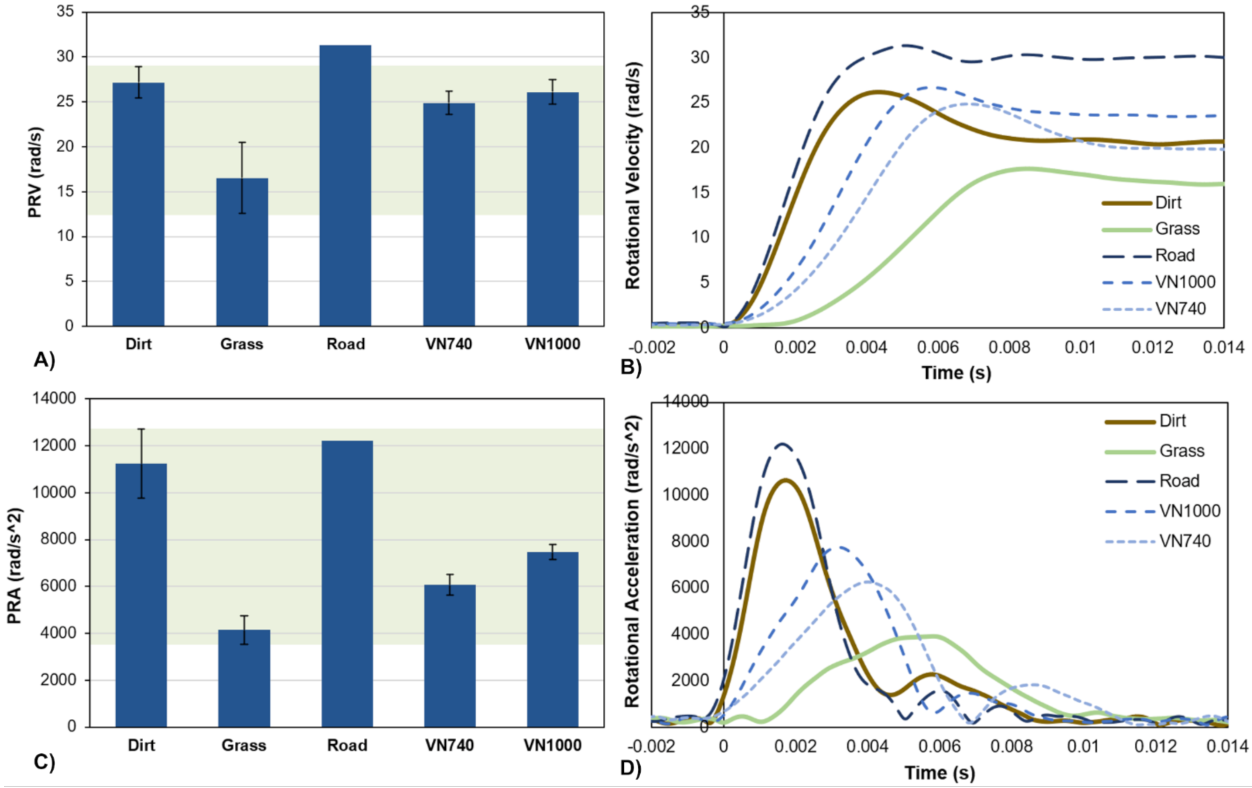

Fig. 4. Oblique impact validation test results. The Dirt and Grass results are from the MTB trail surface testing, while the other results are from matched laboratory testing. The Road results are from tests against the surrogate road surface. All VN foams were tested with turf on the surface. A) and C) show PRV and PRA results, respectively, with the green shaded regions depicting the MTB trail surface range, and B) and D) show example rotational velocity and acceleration data over time, respectively.

The oblique MTB trail surface tests produced average PRVs of 17-27 rad/s and PRAs of 4,147-11,239 rad/s^2 (Fig. 4). Based on the normal impact headform validation results, VN1000 and VN704 foams were used in the oblique impact headform validation testing. High speed video did not show visible slippage of the turf or the foams during impact. Both VN704/turf and VN1000/turf produced PRVs and PRAs that did not differ significantly from the range of oblique MTB trail surface test results (p>=0.2; Fig. 4). The foam/ turf PRVs, which were not significantly different from each other (p=0.32), were 14-19% greater than the average MTB trail surface result. For PRA, the average VN1000/turf and VN704/turf results were 3% and 21% lower than the average MTB trail surface result, respectively. In contrast, the surrogate road PRV and PRA were 44-59% greater than the average MTB trail surface results, although the PRA still fell within the large standard deviation of the dirt PRA results. Comparing the duration and PLA results between the foam/turf anvils and the oblique MTB trail surface tests showed similar trends to the normal impact test results; VN704/turf produced an average duration 32% greater and an average PLA 34% lower than the average MTB trail surface results, while VN1000/turf produced an average duration and PLA that were <8% different from the average MTB trail surface results.

Based on the headform validation testing, the VN1000/turf compliant surface was shown to produce results within the range of all MTB trail surface results and was therefore deemed an appropriate surrogate trail surface. Additional normal and oblique validation tests were conducted on the VN1000 foam with the turf removed. For normal impact tests, non-turf impacts resulted in significantly shorter durations than turf impacts (11%, p=0.02). The average non-turf duration was 10% shorter than the average MTB trail surface duration, whereas the average duration with the turf was <1% different from the average MTB trail surface duration. Removing the turf did not have a significant influence on PLA (3% reduction, p=0.30). For oblique impact tests, non-turf impacts resulted in non-significant differences of 4% greater PRA (p=0.46) and 1% lower PRV (p=0.83) compared to turf impacts.

The VN1000 foam/turf combination was used as the surrogate trail surface for the MTB helmet oblique impact testing protocol. No slippage of the turf or foam was observed in the high-speed video of these impacts. Variance was similar across the surrogate trail and surrogate road surfaces, with CVs <5% for all kinematic metrics except PRA, which produced CVs <11% for both surfaces. Additionally, no significant differences between bare head impacts pre- and post-testing were found for any kinematic metric (p>=0.1), nor was there a significant trend between trial number and kinematic results for impacts on the surrogate trail surface (0.05>R<0.14, p>=0.7).

Unique distributions of kinematic and risk results were found for helmeted impacts against the surrogate trail versus surrogate road surfaces at each location (Fig. 5-9). Generally, the surrogate trail surface produced longer impact durations and lower PLA, PRV, PRA, and P(AIS2) compared to the surrogate road surface. However, these trends were not consistent across impact locations. For frontal impacts, the surrogate trail surface produced 14.6% longer duration (p<0.01), 19.0% lower PLA (p<0.01), 20.9% lower PRV (p<0.01), 35.3% lower PRA (p<0.01), and 36.0% lower P(AIS2) (p<0.01) compared to the surrogate road surface. In contrast, the side impact surrogate trail surface results showed a 6%, non-significant increase in duration (p=0.33), 28.1% lower PLA (p<0.01), 13.4% higher PRV (p<0.01), 17.2% lower PRA (p=0.04), and 33.2% lower P(AIS2) (p<0.01) compared to the surrogate road surface results. Only P(AIS2) was not significantly different across impact location (p=0.13). P(AIS2) was moderate across all impact conditions, ranging from 22-36% on average.

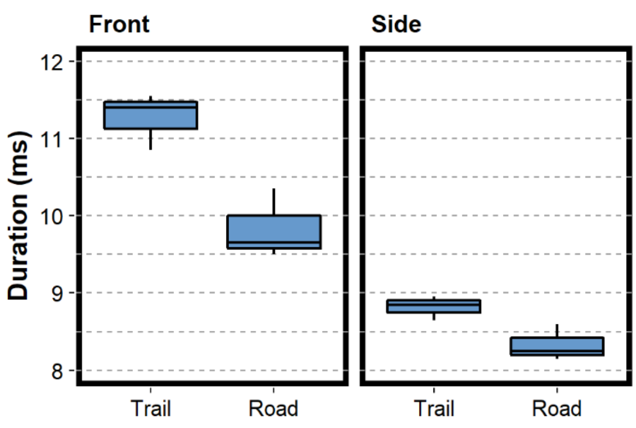

Fig. 5. Impact duration distributions from helmeted oblique impacts at front (left) and side (right) locations onto surrogate trail and surrogate road surfaces.

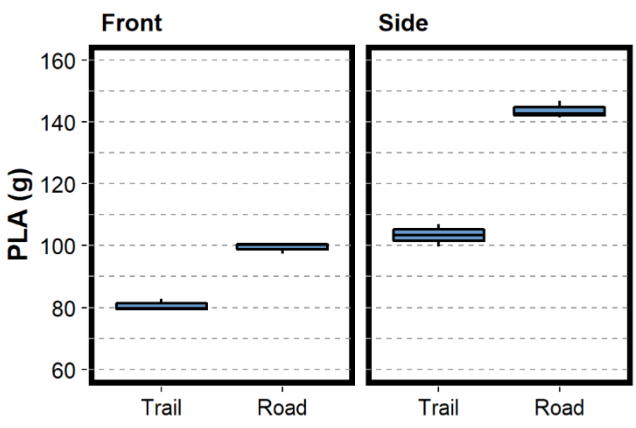

Fig. 6. PLA distributions from helmeted oblique impacts at front (left) and side (right) locations onto surrogate trail and surrogate road surfaces.

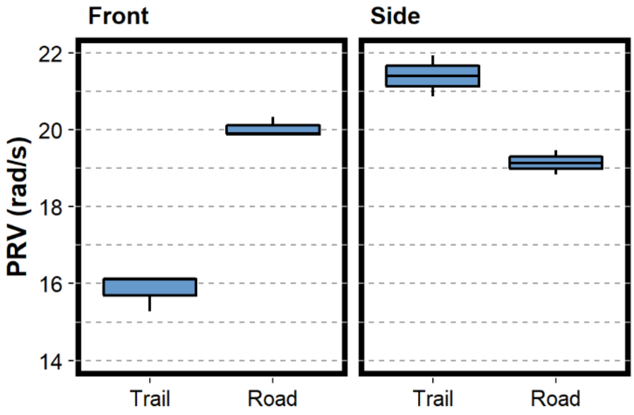

Fig. 7. PRV distributions from helmeted oblique impacts at front (left) and side (right) locations onto surrogate trail and surrogate road surfaces.

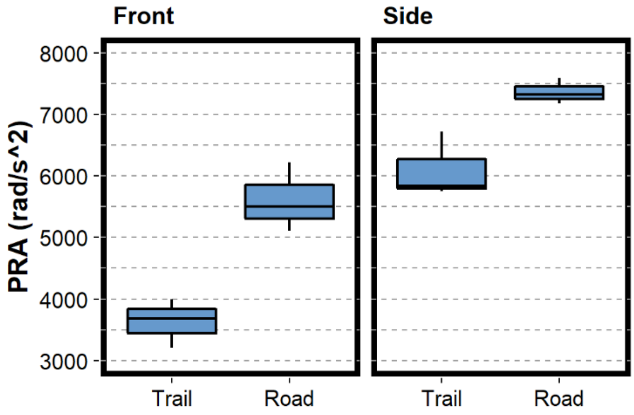

Fig. 8. PRA distributions from helmeted oblique impacts at front (left) and side (right) locations onto surrogate trail and surrogate road surfaces.

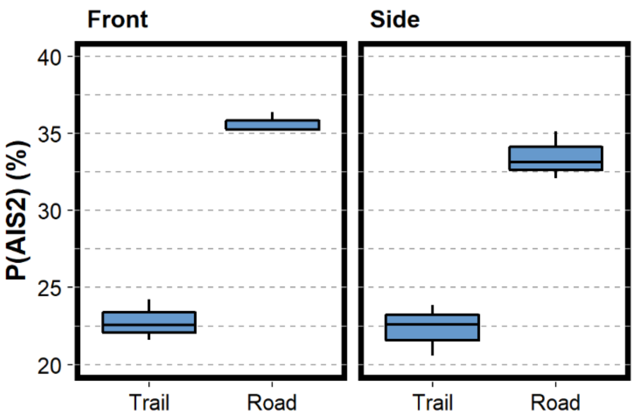

Fig. 9. P(AIS2) distributions from helmeted oblique impacts at front (left) and side (right) locations onto surrogate trail and surrogate road surfaces.

IV. Discussion

Falls onto compliant surfaces are reportedly common in injury-producing MTB crashes [3][5][8]. Therefore, this study developed a framework for laboratory testing of MTB helmets in oblique impacts against surrogate MTB compliant trail surfaces. A headform was impacted against several MTB trail surfaces, and results were compared to matched impact tests against foam surfaces covered with turf. Impacts were also conducted against rigid, high-friction surfaces more reflective of a road environment. The higher linear and rotational kinematics produced by the surrogate road surface, along with the shorter durations, suggest that the conventional anvils used in existing standards and helmet oblique impact studies have higher stiffness and surface friction compared to typical MTB compliant trail surfaces. The VN1000/turf combination was found to better represent the MTB trail surface impact responses and was thus selected as the surrogate trail surface for ensuing helmet testing. Of note, the four foams tested in the headform validation portion of this study were based on those found to represent compliant equestrian surfaces impacts [31-32]. Although VN1000/turf was found to produce impact results within the range of MTB trail surface results and therefore deemed a suitable surrogate trail surface for the present study, future studies could expand the foam selection to identify other options for trail surrogates.

The selection of VN1000/turf as a surrogate trail surface informed the development of a laboratory oblique impact testing method for MTB helmets. The variance associated with helmeted impact testing on the surrogate trail surface was found to be similar to the variance associated with the surrogate road surface, and the surrogate trail surface did not show evidence of degradation over the several dozen tests involved in the present study. These findings indicate that testing on the surrogate trail surface had good repeatability and durability, highlighting its potential usefulness for laboratory testing of helmet impact performance. The durability and repeatability of the surrogate trail surface over greater numbers of tests or at different impact speeds has not been investigated herein, however. This should be explored prior to carrying out larger test series on this surface. Additionally, the presence of the turf did not have a significant influence on the kinematic results aside from duration. Although impacts with the turf produced durations more in line with the average MTB trail surface results, durations from impacts without the turf were still within the overall range of MTB trail surface results. Therefore, it may not be necessary to include turf in future surrogate MTB trail surface testing, especially if researchers would seek to create individual surrogate anvils to represent specific MTB trail surfaces.

In general, PLA and PRA were lower and durations were longer for helmeted impacts against the surrogate trail surface compared to the surrogate road surface. This finding was expected since compliant surfaces by nature deform and absorb energy upon impact, lowering the peak impact force and extending the contact time. However, impact durations were not exceptionally high for the helmeted surrogate trail surface impacts; the 8.8-11.3 ms range in average duration produced by the surrogate trail surface falls within the range of those reported for helmeted head impacts against rigid anvils [36][40]. The durations produced by the surrogate trail surface were also not as long as those reported by [31-32] from helmeted impacts against surfaces in equestrian sports (15-30 ms). As such, the mechanism that [31] describes of high brain strains resulting from longer duration loading are likely not as relevant for the present results. Notably, despite P(AIS2) brain injury risks being significantly lower for the surrogate trail surface compared to the surrogate road surface, the overall risk levels were still moderate. This suggests that there is clinical relevance to investigating MTB helmet performance using compliant surface testing.

Although most kinematic results were lower for the helmeted impacts against the surrogate trail surface versus the surrogate road surface, these trends varied by impact location. Most notably, PRV results were higher on the surrogate trail surface than the surrogate road surface at the side impact location. This finding is likely related to the relative headform orientation and reduced surface friction for this impact condition. High speed video revealed that the head rotated primarily about its X-axis upon impact, likely owing to the offset of the head CG from the initial helmet contact location (Fig. 10A). The higher friction at the helmet-surrogate road surface interface appeared to restrict the ability of the helmet to rotate about the X-axis, whereas the lower friction at the helmet-surrogate trail surface interface allowed the helmet to slip on the turf and facilitated greater rotation about the X-axis, resulting in a higher overall PRV. This is confirmed by the directional rotational velocity curves (Fig 10B). Instead, the road surface produced greater rotation about the Z-axis as the head rolled down the inclined surface of the anvil under the influence of gravity (Fig. 10A). These altered loading patterns likely account for the non-significant difference in duration at this location as well. The distinct responses of the helmet on the surrogate trail surface versus the surrogate road surface for certain impact locations could have implications for how rotation-mitigation technology is designed for MTB helmets. Interestingly, despite the PRVs at the side location on the surrogate trail surface being the highest PRVs of all helmeted head impacts in the present study, P(AIS2) was still lower for the surrogate trail surface compared to the surrogate road surface at this location. This is due to the underlying BrIC equation, which uses higher tolerance values for X-axis rotation compared to Z-axis rotation to reflect the greater sensitivity of the brain to injury from rotation about the Z-axis [38].

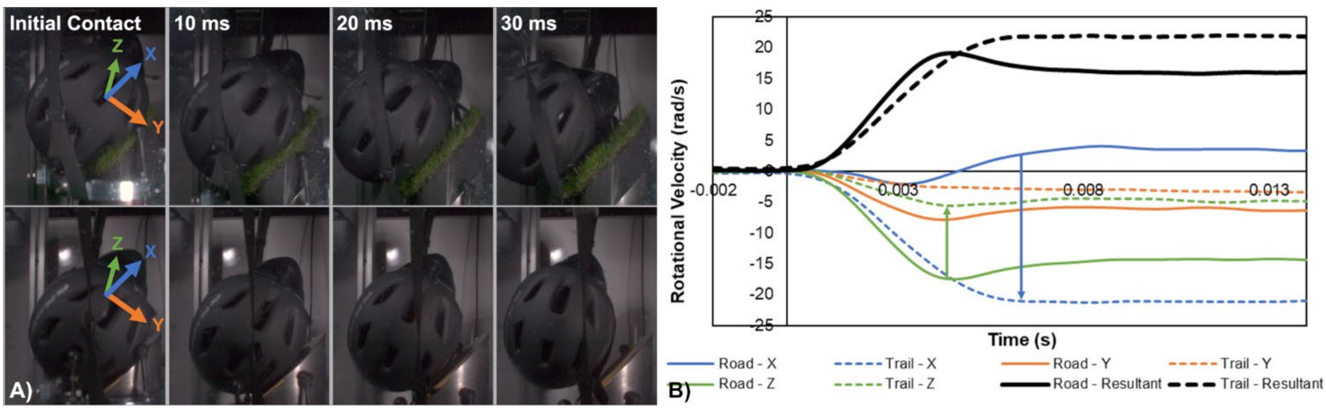

Fig. 10. A) Still-frame images of side impact tests on surrogate trail (top) and surrogate road (bottom) surfaces illustrating the headform/helmet rotational trajectory during and after impact. Surrogate trail impacts caused primary rotation about the X-axis (anterior-posterior axis), while surrogate road impacts caused primary rotation about the Z-axis (superior-inferior axis), B) Example rotational velocity data for a side impact on surrogate road and trail surfaces. The surrogate trail surface showed an increase in X-axis response (blue arrow) and a decrease in Z-axis response (green arrow) compared to the surrogate road surface.

The testing approach for oblique impacts against a surrogate trail surface developed herein can be used for future MTB helmet evaluation. This testing can serve as a supplement to the rigid surface impact testing of MTB helmets employed by current standards and oblique testing protocols, enabling an understanding of how MTB helmets perform in both compliant and rigid impact conditions. Although falls on compliant surfaces are reportedly more common in MTB [3][5][8], impacts against rigid surfaces are certainly still possible, and therefore it is important to continue to design MTB helmets around these higher force impact conditions. A benefit of the protocol developed in the present study is that the impact conditions reflect a subset of those specified in the VT STAR protocol [27]. If manufacturers have MTB helmets that have been subjected to VT STAR evaluation, they could then recreate the proposed surrogate trail surface testing with said helmets and conveniently compare results to surrogate road surface impact results from the VT STAR testing. This approach can help to ensure that multiple features of MTB helmets, such as characteristics of the energy absorbing liner or rotation-mitigating technologies, are evaluated in a more realistic spectrum of impact conditions that may be encountered in MTB.

There are several limitations that should be considered when interpreting the present results. First, this study did not quantify the intrinsic material properties of MTB trail surfaces or the materials used as surrogates; rather, the outcome of impacts against these surfaces was used for validation. This approach reflects the ASTM F355-16 standard for measuring impact attenuation of sport- and recreation-related ground surfaces [41]. Nonetheless, further characterisation of the present impact surfaces can provide greater confidence in the surrogate selection. This could include using high-speed video of MTB trail surface testing to investigate dislodging of ground material during impact. Additionally, validation testing was conducted using a bare headform rather than a helmeted headform in an effort to minimize variance in this dataset. As the addition of a helmet modifies impact characteristics, conducting additional validation tests with a helmet would also increase confidence in the helmeted impact results. Another limitation is that a single surrogate trail surface was chosen to represent mid-range MTB trail surface results rather than identifying individual surrogates to represent dirt or grass specifically. This approach was selected in part because one surrogate trail surface was deemed to be sufficient for uncovering trends in helmet performance between rigid and compliant surface tests, and in part due to the limited number of tested MTB trail surfaces and weather conditions. Validation testing could be expanded in future studies to quantify impact characteristics of a larger range of MTB trail surfaces, enabling creation of more specific surface surrogates if desired. This could include surfaces with many rocks and/or roots, which studies suggest are also common crash surfaces in MTB [3][5][8], although rigid hemispherical or kerbstone anvils used in standards may represent properties of rocks or roots reasonably well. An additional limitation is that the VN1000/turf anvil used herein was also only validated at 4.8 m/s. Conducting validation testing at higher speeds may be especially relevant for downhill mountain biking, where riders can attain higher travel speeds [5][6-8].

Finally, several limitations of the present study pertain to the VT STAR test method that was reflected herein [27]. Although a steel anvil coated with 80-grit sandpaper is a common setup for representing a road surface in oblique impact helmet testing [30], [39] showed that the stiffness and friction properties of this setup may be higher than common road surfaces. Additionally, the helmet visor was removed prior to testing in accordance with VT STAR testing. Visors come on virtually all MTB helmets, so it would be worthwhile to investigate the effects of a visor in future testing. The VT STAR protocol also does not include a surrogate neck. Testing without a neck is common in oblique impact bicycle helmet testing [25][27][29], with the limited biofidelity of the widely used Hybrid III neck in axial compressive loading often cited as a primary reason for forgoing a neck [27][29][42]. Still, oblique impact helmet testing using the Hybrid III neck is also common [14][26][43], with proponents of this testing approach citing the effects of human necks on head impact dynamics [43-44]. Future studies should expand the present testing approach to include test methods with an appropriate head and neck setup as well.

V. CONCLUSIONS

This study details the investigation of a laboratory method for evaluating MTB helmets in oblique impacts against a surrogate compliant MTB trail surface. The surrogate trail surface was comprised of a VN foam anvil covered with turf and was validated based on headform impact tests against dirt and grass surfaces at local MTB trails. Testing also showed that impacts against a rigid surface more similar to a road produced accelerations that were very high and durations that were very short compared to MTB trail surfaces. A method for helmet oblique impact testing against the surrogate trail surface was then carried out using a conventional MTB helmet, which was also tested in matched impacts against a surrogate road surface. Although most kinematic results and predicted brain injury risks were lower for the surrogate trail surface compared to the surrogate road surface, trends varied by impact location, with higher PRVs observed on the surrogate trail surface versus the surrogate road surface for one location. Such location-specific differences in helmet impact response across surrogate trail and road surfaces, coupled with the overall moderate predicted brain injury risks, suggests that conducting both rigid and compliant surface testing could provide a valuable framework for evaluating the rotational performance of MTB helmets. Manufacturers and researchers alike could use this testing to supplement rigid impact testing, allowing investigation of MTB helmet performance under a broader array of relevant impact conditions.

VI. REFERENCES

[1] Fiore D, Fellows KM, Henner TA. Injuries in Mountain Biking and Implications for Care. *Muscle Ligaments and Tendons Journal*, 2020, 10(2): 179-191.

[2] Outdoor Foundation. (2022) Outdoor Foundation, 2022 Outdoor Participation Trends Report.

[3] Becker J, Runer A, Neunhäuserer D, Frick N, Resch H, Moroder P. A Prospective Study of Downhill Mountain Biking Injuries. *British Journal of Sports Medicine*, 2013, 47(7): 458–462.

[4] Palmer D, Florida-James G, Ball C. Enduro World Series (EWS) Mountain Biking Injuries: A 2-Year Prospective Study of 2010 Riders. *International Journal of Sports Medicine*, 2021, 42(11): 1012–1018.

[5] Chow TK, Bracker MD, Patrick K. Acute Injuries From Mountain Biking. *The Western Journal of Medicine*, 1993, 159(2): 145–148.

[6] Chow TK, Kronisch RL. Mechanisms of Injury in Competitive Off-Road Bicycling. *Wilderness & Environmental Medicine*, 2002, 13(1): 27–30.

[7] Kronisch RL, Chow TK, Simon LM, Wong PF. Acute Injuries in Off-Road Bicycle Racing. *The American Journal of Sports Medicine*, 1996, 24(1), 88–93.

[8] Kronisch RL, Pfeiffer RP. Mountain Biking Injuries: An Update. *Sports Medicine*, 2002, 32(8): 523–537.

[9] Ashwell ZA, McKay MP, Brubacher JR, Gareau A. The Epidemiology of Mountain Bike Park Injuries at the Whistler Bike Park, British Columbia (BC), Canada. *Wilderness & Environmental Medicine*, 2012, 23: 140–145.

[10] Sharma VK, Rango J, Connaughton AJ, Lombardo DJ, Sabesan VJ. The Current State of Head and Neck Injuries in Extreme Sports. *Orthopaedic Journal of Sports Medicine*, 2015, 3(1): 1-6.

[11] Thompson DC, Rivara FP, Thompson RS. Effectiveness of Bicycle Safety Helmets in Preventing Head Injuries: A Case-Control Study. Journal of the American Medical Association, 1996, 276(24): 1968-1973.

[12] McDermott FT, Lane JC, Brazenor GA, Debney EA. The effectiveness of bicyclist helmets: a study of 1710 casualties. *The Journal of Trauma*, 1993, 34(6):834-844.

[13] Cripton PA, Dressler DM, Stuart CA, Dennison CR, Richards D. Bicycle Helmets Are Highly Effective at Preventing Head Injury during Head Impact: Head-Form Accelerations and Injury Criteria for Helmeted and Unhelmeted Impacts. *Accident Analysis & Prevention*, 2014, 70: 1–7.

[14] McIntosh AS, Lai A, Schilter E. Bicycle Helmets: Head Impact Dynamics in Helmeted and Unhelmeted Oblique Impact Tests. *Traffic Injury Prevention*, 2013, 14(5): 501–8.

[15] CPSC. (1998) United States Consumer Product Safety Commission, *16 CFR Part 1203 Safety Standard for Bicycle Helmets Final Rule*.

[16] CEN. (2012) European Committee for Standardization, *EN 1078 2012+A1:2012 Helmets for pedal cyclists and for users of skateboards and roller skates*.

[17] ASTM. (2015) American Society for Testing and Materials, *ASTM F1952-15: Helmets Used for Downhill Mountain Bicycle Racing*.

[18] Peng Y, Chen Y, Yang J, Otte D, Willinger R. A study of pedestrian and bicyclist exposure to head injury in passenger car collisions based on accident data and simulations. *Safety Science*, 2012, 50(9): 1749–1759.

[19] Bourdet N, Deck C, Carreira RP, Willinger R. Head impact conditions in the case of cyclist falls. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 2012, 226(3-4): 282–289.

[20] Bourdet N, Deck C, Serre T, Perrin C, Llari M, Willinger R. In-depth real-world bicycle accident reconstructions. *International Journal of Crashworthiness*, 2014, 19(3): pp. 222–32.

[21] Bland ML, McNally M, *et al*. Laboratory Reconstructions of Bicycle Helmet Damage: Investigation of Cyclist Head Impacts Using Oblique Impacts and Computed Tomography. *Annals of Biomedical Engineering*, 2020, 48(12): 2783-2795.

[22] Gennarelli T, Ommaya A, Thibault L. Comparison of translational and rotational head motions in experimental cerebral concussion. *Proceedings of 15th Stapp Car Crash Conference*, 1971, New York, USA.

[23] Gennarelli TA, Thibault LE, Ommaya AK. Pathophysiologic responses to rotational and translational

accelerations of the head. *SAE Technical Paper Series*, 1972, 720970: 296–308.

[24]Ommaya A, Hirsch A. Tolerances for cerebral concussion from head impact and whiplash in primates. *Journal of Biomechanics*, 1971, 4(1): 13–21.

[25]Stigson H, Rizzi M, Ydenius A, Egnstrom E, Kullgren A. Consumer Testing of Bicycle Helmets. *Proceedings of IRCOBI Conference*, 2017, Antwerp, Belgium.

[26]Bliven E, Rouhier A, *et al*. Evaluation of a Novel Bicycle Helmet Concept in Oblique Impact Testing. *Accident Analysis & Prevention*, 2019, 124: 58–65.

[27]Bland ML, McNally C, Zuby DS, Mueller BC, Rowson S. Development of the STAR Evaluation System for Assessing Bicycle Helmet Protective Performance. *Annals of Biomedical Engineering*, 2020, 48(1): 47-57.

[28]Chow TK, Corbett SW, Farstad DJ. Do Conventional Bicycle Helmets Provide Adequate Protection in Mountain Biking? *Wilderness & Environmental Medicine*, 1995, 6(4): 385–390.

[29]Abayazid F, Ding K, Zimmerman K, Stigson H, Ghajari M. A New Assessment of Bicycle Helmets: The Brain Injury Mitigation Effects of New Technologies in Oblique Impacts. *Annals of Biomedical Engineering*, 2021 49(10): 2716–33.

[30]ECE. R-22.06: Uniform provisions concerning the approval of protective helmets for drivers and passengers of motorcycles and mopeds. United Nations Economic Commission for Europe, 2021.

[31]Clark JM, Connor TA, Post A, Hoshizaki TB, Annaidh AN, Gilchrist MD. Could a Compliant Foam Anvil Characterize the Biofidelic Impact Response of Equestrian Helmets? *Journal of Biomechanical Engineering*, 2020, 142(6): 061006-1-9.

[32]Clark JM, Hoshizaki TB, Annaidh AN, Gilchrist MD. Equestrian Helmet Standards: Do They Represent Real-World Accident Conditions? *Annals of Biomedical Engineering*, 2020, 48(8): 2247–2267.

[33]Cenek PD, Jamieson NJ, McLarin MW. (2005) Opus International Consultants, Central Laboratories, *Frictional characteristics of roadside grass types*, Gracefield, New Zealand.

[34]SAE. (2022) Society of Automotive Engineers, *SAE J211/1_202208 Instrumentation for Impact Test Part 1 - Electronic Instrumentation*.

[35]Cobb BR, Tyson AM, Rowson S. Head acceleration measurement techniques: reliability of angular rate sensor data in helmeted impact testing. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 2017, 232:176–181.

[36]Bland ML, McNally C, Rowson S. Headform and Neck Effects on Dynamic Response in Bicycle Helmet Oblique Impact Testing. *Proceedings of IRCOBI Conference*, 2018, Athens, Greece.

[37]"Pinkbike Friday Fails", Internet: www.pinkbike.com/news/tags/friday-fails/. [August 2021]

[38]Takhounts EG, Craig MJ, Moorhouse K, McFadden J, Hasija V. Development of Brain Injury Criteria (BrIC). *Stapp Car Crash Journal*, 2013, 57: 243-266.

[39]Bonugli E, Cormier J, Reilly M, Reinhart L. Replicating Real-World Friction of Motorcycle Helmet Impacts and Its Effects on Head Injury Metrics. *SAE Technical Paper Series*, 2017, 2017-01-1433.

[40]Bland ML, Zuby DS, Mueller BC, Rowson S. Differences in the protective capabilities of bicycle helmets in real-world and standard-specified impact scenarios, *Traffic Injury Prevention*, 2018, 19(sup1): S158-S163.

[41]ASTM. (2016) American Society for Testing and Materials, *ASTM F355-16: Standard Test Method for Impact Attenuation of Playing Surface Systems, Other Protective Sport Systems, and Materials Used for Athletics, Recreation and Play*.

[42]Sances AJ, Carlin F, Kumaresan S. Biomechanical analysis of head-neck force in Hybrid III dummy during inverted vertical drops. *Biomedical Sciences Instrumentation*, 2002, 38: 459–64.

[43]Chung VWJ, Dias L, Booth G, Cripton PA. Incorporating Neck Biomechanics in Helmet Testing: Evaluation of Commercially Available WaveCel Helmets. *Clinical Biomechanics*, 2022, 94(105628): 1-9.

[44]Ghajari M, Peldschus S, Galvanetto U, Iannucci L. Effects of the presence of the body in helmet oblique impacts. *Accident Analysis & Prevention*, 2013, 50: 263–71.