An Evaluation of the Protective Performance of a Motocross Helmet with and without Rotational Mitigating Technology Under Impacts Representing Real-world Impact Surface Conditions

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Abstract Motocross racing involves high speeds and rough terrain, including asphalt, gravel and dirt. This environment, along with complex race circuits, creates conditions that pose risk for head and brain injuries, including concussions. With the inclusion of a rotational energy component to safety certification criteria for motorcycle helmets, rotational mitigating technologies are present in some helmets, aimed at reducing the rotational motion transferred to the head. This study examined the influence of ground surface materials that could be found in motocross environments, on the head dynamic response, and the performance of a motocross helmet with and without rotational mitigating technology was evaluated. Surfaces of concrete with 80-grit paper, and mixed gravel, produced the highest head and brain response and were used to evaluate helmet performance. A Hybrid III headform with helmet was launched at 7.5 m/s at a 45° angle to front- and side-impact sites. Head linear and rotational acceleration and rotational velocity were measured, and THUMS was used to calculate the 95th maximum principal strain. Results showed that helmets with rotational technology reduced resulting head rotational components and strain to brain tissues. This study highlights the value of including rotational mitigating technology in motocross helmets to reduce the risk of injury.

Keywords Helmet performance, motocross, real-world test conditions, rotational mitigating technology, surface condition.

I. INTRODUCTION

Motocross (MX), a class of off-road dirt bike riding, has participants around the world and is popular in North America and Europe. MX is an exciting sport involving high speeds and 25–30 riders navigating tight race circuits that include jumps, corners, obstacles and rough surface terrain. These surroundings, coupled with a competitive environment, create conditions for accidents, which often impact the head. The number of injuries linked to high-impact sports, such as motocross, has risen in tandem with increased participation [1-2]. Helmets play an important role for participants, to protect them within the racing environment.

Advances in helmet engineering have decreased the severity of head and brain injury outcomes and improved protection against life-threatening injuries [3]. This has shifted the primary risk to non-fatal injuries, including concussions, which are a common injury among motor sport riders [4-5]. During competitive events, reports estimate that MX riders sustain concussions ranging from 9.5% to 19.1% [6-8]. In young riders, reports show that close to 50% of competitors under 18 years of age have experienced at least one self-reported concussion symptom [6]. Considering the potentially adverse long-term neurobehavioural consequences following one or multiple concussion diagnoses, this raises concerns for young athletes.

Motor sport helmets are required to pass testing protocols to meet safety requirements and approval from certification bodies (e.g., FIM, SNELL, DOT, ECE). Safety performance is evaluated using criteria based on head linear acceleration during vertical drop impacts, ensuring this type of energy attenuation system is built into the design of the helmet. However, impacts to the head also create a rotational component of acceleration, which has a significant association with concussive brain injury caused by deformation of brain tissues within the skull [9-11]. With the adoption of two test standards for sport helmets that include a rotational head acceleration component [12-13], helmet designs now incorporate technology to attenuate rotational energy.

The performance of rotational helmet technology is evaluated using oblique impact conditions involving

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vertical drop systems [14-16] or finite element (FE) modeling of the head/helmet complex [17]. Yu and colleagues [14] tested the performance of motorcycle helmets with various rotational management systems under oblique impact conditions using a drop system. Their results showed a reduction in injury risk among helmets with rotational technologies compared to the conventional helmets. Reductions in injury metrics and brain strain were variable among the helmets with rotational management systems and influenced by the conditions of the impacts tested. Similarly, DiGiacamo and colleagues [16] investigated the efficacy of two rotation-dampening systems, Mips and WaveCel, applied in snow sport helmets. They conducted vertical drop tests on a 45° anvil coated with 80-grit paper. Their findings highlighted the effectiveness of these rotation-dampening systems in reducing rotational head acceleration during the oblique impacts tested.

These studies demonstrate the efficacy of rotational technologies, but also highlight that an important consideration when evaluating helmet performance is the condition of the head impact event, including speed, head impact location, surface compliance and the mechanism of injury [18-19]. Accident reconstruction methods in a controlled laboratory afford an opportunity to evaluate helmet performance during impact scenarios that represent the conditions found within the sport environment, including surface conditions [20-22]. Clark *et al*. [20] reconstructed concussive events occurring in equestrian falls by simulating the mechanisms, speeds and surfaces in the laboratory. This group employed a rail-guided launcher (RGL) to simulate realistic head impact mechanics of falling and hitting the ground created from falling forward from something in motion, such as occurs in cycling, equestrian riding, and motorcycle accidents [23]. Their research demonstrated the importance of considering surface compliance in creating risk for concussive events, and they recommended the inclusion of multiple surfaces in industry safety certification standards.

Murphy *et al*. [19] employed a similar protocol to examine the efficacy of the inclusion of rotational technology in equestrian helmets under realistic impact scenarios associated with risk of concussion. Their protocol employed the RGL to replicate a falling mechanism experienced by riders at high speeds. Their results demonstrated that the presence of rotational technology reduced head accelerations, however the effect was dependent on the impact conditions of the event. Their findings revealed the importance of ground surface conditions in managing risk to injury using rotational technology. Specifically, their results showed variable efficacy in reducing head rotational components between compliant and non-compliant surfaces. The purpose of this study had two phases: A) to investigate different material surfaces found within the MX environment to establish a protocol for testing helmet performance, and B) to test the performance of a rotational management technology under impact conditions that represent real-world impact mechanisms and material surfaces found in MX environments and accidents.

II. METHODS

Experimental Testing

The impact tests were performed using an RGL. The RGL simulates falling from something in motion in contrast to vertical drops and was used to test surface material and helmet performance under conditions that reflect real-world accidents [23]. The system consists of a steel carriage to anchor and guide the headform, which was released at an angle of 20° towards the impact surface positioned at 25° to the ground, for a total impact angle of 45°, representing the average impact angle reported by Bourdet *et al.* [24]. For all experimental testing, a 50th percentile adult male Hybrid III headform (4.54 ± 0.01 kg) equipped with a Diversified Technical System (DTS) 6DX PRO attached to a SLICE NANO free motion data acquisition system was used. The system includes a triaxial accelerometer to measure linear acceleration and three angular rate sensors to measure rotational velocity positioned at the head's centre of gravity. Rotational acceleration was obtained from the time derivative of the measured rotational velocity time-histories. The headform was released from the carriage from a height of 0.51 m from the ground at an impact velocity of 7.5 ± 0.07 m/s, measured using a high-speed camera. The accelerometer and angular rate sensors were sampled at 20 kHz and subsequently filtered with a 300 Hz low pass Butterworth filter (CFC 180) in accordance with the SAE J211 convention [25]. The data collected consisted of linear acceleration (measured in g), rotational acceleration (measured in rad/s^2), and rotational velocity (measured in rad/s) time histories across the *x*, *y* and *z* axes of the headform. The head response time curves were used as input to the Total Human Models for Safety (THUMS) for brain response analysis, which is further described below.

Fig. 1. Rail-guided launcher (RGL) used for all head impacts. Consists of adjustable rails and a steel carriage to anchor and guide the headform.

Phase A: Surface Material Impact Method

To establish a surface material impact method, a range of ground surface conditions were tested to represent possible terrain experienced in MX racing. Five surface materials were tested, including concrete, sand, crushed stone, dirt and mixed gravel (Fig. 2). Ground material surfaces of crushed stone, sand, dirt and mixed gravel were created using a large wooden box (0.91 m x 0.48 m x 0.20 m) filled with each material, which was placed on a metal ledge and securely attached using strong double-sided tape to a steel anvil bolted to a cement floor (Fig. 2). The material was compacted and smoothed out using a flat shovel before each impact trial. The concrete anvil consisted of a square patio slab, securely attached using metal clamps to a steel anvil bolted to a cement floor (Fig. 2). The weight, volume and condition of the materials are provided in Table I. For all impacts, the headform was fitted with a medium size oxelo MF 500 skate helmet with EPS liner and ABS shell. This helmet was chosen as it is a lightweight, full-coverage model with ventilation located along the top portion of the helmet. Unlike MX helmets, the shape of this helmet is a smooth rounded shell with no geometrical groves, allowing the experimental impact tests to isolate the difference in material surface by removing the additional influence of helmet shape. The helmet was placed on the headform with 10.2 cm from the tip of the nose to the front bottom edge of the helmet which was in accordance with the image provided in the manufacturer's helmet position index (HPI). Impacts were performed to a front site (8.9 cm above the front bottom edge of the helmet in the sagittal plane) on the head/helmet for five impact trials, using a new helmet for each trial and ground surface material. To ensure consistency in the impact site, distance measurements were used and checked for each impact trial.

Fig. 2. Impact surfaces tested including: A. concrete, B. sand, C. crushed stone, D. dirt and E. mixed gravel.

TABLE I
IMPACT SURFACES

Material	Description	Weight (kg)	Volume (ft^3)	Conditioning
Concrete	square patio slab	15.8	0.251	dry
Sand	natural play sand	100	2.137	packed dry
Crushed stone	crushed rock ¼ - ½"	90	2.137	500 ml water added
Dirt	black earth	26.3	2.137	packed black earth
Mixed gravel	0 – ¾"	98.5	2.137	500 ml water added

Phase B: Helmet Performance Impact Procedure

The performance of an MX helmet with and without rotational technology was evaluated using concrete and mixed gravel surfaces, chosen to represent the highest head and brain response from the materials tested in Phase A (*see* surface material results in Table III). For MX helmet tests, the concrete anvil was covered with a piece of 80-grit paper, consistent with previous helmet comparison studies [26-27]. The MX helmets tested met certification standards of DOT and ECE 22.05. All helmets were a size medium 2021 Fox Racing V3 RS helmet with a circumference of 60 cm comprised of a lightweight carbon composite shell and a dual-density EPS foam liner. Helmets with rotational technology were an identical make/model with an additional component of a Multi-Directional Impact Protection System (Mips) (Fig. 3). The helmet was placed on the headform with 6.4 cm from the tip of the nose to the front bottom edge of the helmet and the D-rings and chin strap was fitted in accordance with the fastening instructions and figure provided in the manufacturer's HPI. Impacts were performed to a front site (located 10.2 cm above the front edge of the helmet in the sagittal plane) and side site (located 20.3 cm above the front edge of the helmet in the sagittal plane and 11.4 cm towards the right side in the frontal plane) on the head/helmet. Three impact trials were performed to the front- and side-impact sites, using a new helmet for each site, trial and ground surface material. Again, to ensure the consistency in impact sites, distance measurements were used and checked before each impact trial.

Fig. 3. MX helmet tested with (left) and without (right) rotational mitigating technology.

Computational Modeling

The head response time curves for each impact trial for the skate and MX helmet tests were used as input to the THUMS for brain tissue analysis [28]. The brain material properties of this model are linear viscoelastic with standard linear solid and element formulation is eight-node brick element with constant stress. The model has automatic surface to surface between pia sagittal – falx and brain – tentorium and continuous mesh between brain and subdural cerebrospinal fluid (CSF). Further details on this model are presented in Table II. The 3-dimensional head linear acceleration and rotational acceleration were applied to the centre of gravity of THUMS to calculate the magnitude of brain tissue strain. Specifically, the maximum principal strain (MPS) was calculated using Equation 1:

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$$\varepsilon 1, 2 = (\varepsilon x + \varepsilon y + \varepsilon z)/3 \pm \sqrt{2}/3\sqrt{(\varepsilon x - \varepsilon y)^2 + (\varepsilon y - \varepsilon z)^2 + (\varepsilon z - \varepsilon x)^2} \quad (1)$$

where ε x, ε y and ε z are strains measured along corresponding axes. The peak value MPS in each element for the whole brain were extracted and the 95th percentile (MPS95) values are presented and compared.

Statistical Analysis

Differences in helmet performance between the helmet with and without rotational technology was evaluated using two-tailed t-tests for equal variance, with statistical alpha level of 0.05. Analyses compared head and brain response resulting from impact conditions, including two ground surface materials and two impact sites.

TABLE II
THUMS PROPERTIES

Model Characteristic	#
Brain elements	118.8 k
Brain nodes	128.2 k
Brainstem elements	1682
Brainstem nodes	2197
Intracranial volume [dm^3]	1.6

III. RESULTS

Phase A

The results of Phase A of this study, namely the average (SD) head dynamic response measures of peak linear acceleration, peak rotational acceleration, peak rotational velocity and brain strain of MPS95 resulting from skate helmeted impacts to five ground surface materials are presented in Table III (*see* impact trial results Appendix A). Impacts to concrete consistently resulted in the highest response for all head and brain response measures, followed by head impacts to the ground surface material of mixed gravel. The most compliant ground materials, dirt and sand, resulted in the lowest responses and longest duration impacts. Sample traces of the resultant head dynamic response over time for the helmeted impacts to five ground materials are presented in Fig. 4, and images of each ground surface material during the impact are presented in Fig. 5. The images presented do not represent the same time point during the impact but rather were chosen based on the observed changes in material to demonstrate the compliance of each material.

TABLE III
HEAD DYNAMIC RESPONSE AND BRAIN STRAIN MEASURES AVERAGED (SD) ACROSS 5 IMPACT TRIALS TO 5 SURFACE MATERIALS

Material	Peak Linear Acceleration, g mean (± SD)	Peak Rotational Acceleration, rad/s^2, mean (± SD)	Peak Rotational Velocity, rad/s mean (± SD)	Peak MPS95 mean (± SD)
Concrete	138.0 (6.9)	7330.7 (505.6)	27.5 (1.1)	0.303 (0.010)
Sand	47.1 (5.0)	2287.0 (261.0)	9.5 (0.6)	0.093 (0.006)
Crushed stone	50.0 (9.7)	1843.8 (335.7)	11.5 (1.6)	0.098 (0.016)
Dirt	25.5 (2.2)	863.7 (51.0)	11.0 (0.8)	0.060 (0.005)
Mixed gravel	98.8 (5.8)	4595.3 (279.8)	23.1 (1.9)	0.253 (0.023)

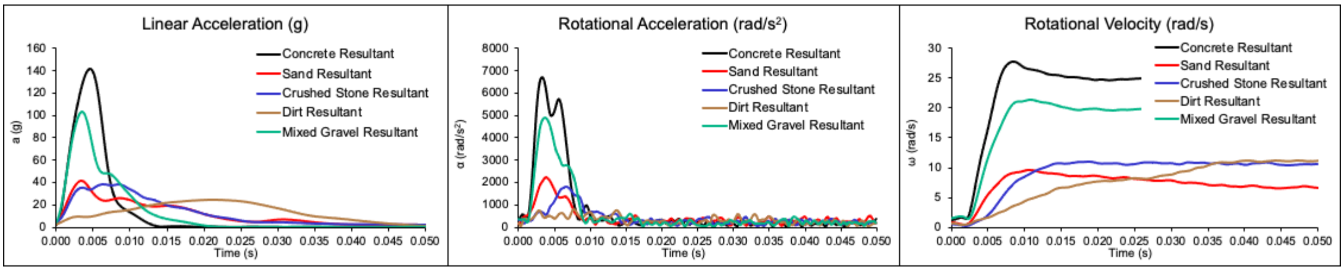

Fig. 4. Sample traces of results for head impacts using a skate helmet to 5 ground surface materials displaying, from left to right, resultant linear acceleration, resultant rotational acceleration and resultant rotational velocity.

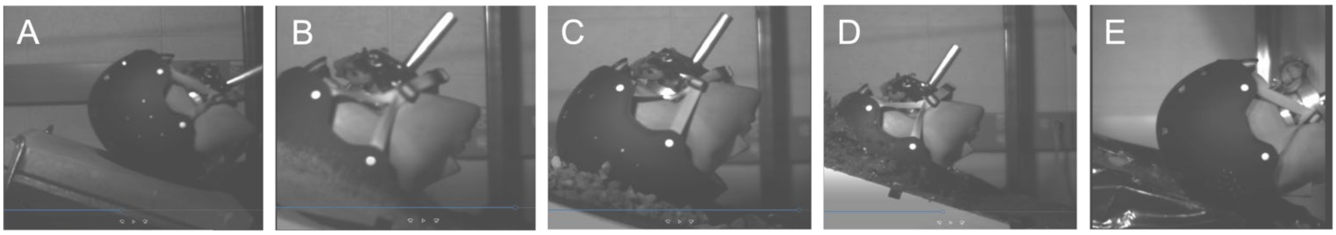

Fig. 5. Images of ground surface material during an impact to: A. concrete, B. sand, C. crushed stone, D. dirt and E. mixed gravel.

Phase B

The results of Phase B of this study, including the average (SD) head dynamic response measures of peak linear acceleration, peak rotational acceleration, peak rotational velocity and brain strain of MPS95 from MX helmeted impacts, are presented in Table IV (*see* impact trial results Appendix A). The impacts to concrete surface consistently resulted in higher head dynamic response and brain tissue strain measures when compared to the mixed gravel surface condition. This was consistent for both front and side impact sites and helmets with and without Mips. Sample traces of the resultant head dynamic response over time for the MX helmeted impacts, are presented in Fig. 6.

TABLE IV
HEAD DYNAMIC RESPONSE AND BRAIN STRAIN MEASURES FOR MX HELMETED IMPACTS WITH AND WITHOUT MIPS AVERAGED (SD) ACROSS 3 IMPACT TRIALS TO FRONT AND SIDE SITE ONTO MIXED GRAVEL AND CONCRETE SURFACES

Material	Impact Site	Linear Acceleration (g)		Rotational Acceleration (rad/s^2)		Rotational Velocity (rad/s)		MPS95	
		Mips	*No Mips*	*Mips*	*No Mips*	*Mips*	*No Mips*	*Mips*	*No Mips*
Mixed Gravel	Front	98.3	97.4	2944.0	3324.2	18.6	21.7	0.180	0.217
		(8.9)	(2.3)	(93.4)	(598.7)	(0.7)	(1.4)	(0.005)	(0.014)
	Side	80.0	78.8	3163.3	4967.3	15.7	20.4	0.150	0.210
		(7.3)	(6.6)	(550.5)	(371.8)	(2.4)	(1.6)	(0.020)	(0.020)
Concrete	Front	126.1	130.1	4578.4	6002.7	26.9	29.8	0.290	0.328
		(1.7)	(2.1)	(475.2)	(164.8)	(0.5)	(0.6)	(0.012)	(0.006)
	Side	115.9	115.3	5352.4	6639.2	20.5	21.7	0.210	0.240
		(3.2)	(3.1)	(154.1)	(396.6)	(0.2)	(1.7)	(0.000)	(0.010)

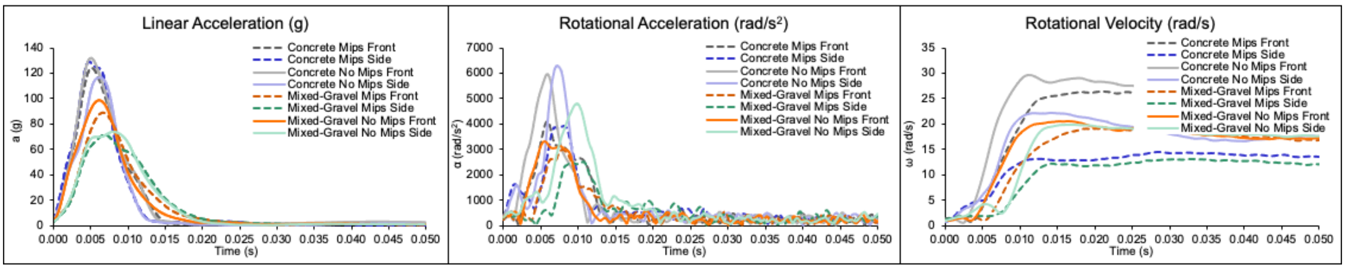

Fig. 6. Example traces of resulting curves for head impacts using an MX helmet with and without Mips to 2 ground surface materials to front and side sites displaying, from left to right, resultant linear acceleration, resultant rotational acceleration and resultant rotational velocity.

T-test results comparing an MX helmet with and without rotational technology under two ground surface materials for two impact sites are displayed in Fig. 7. No significant difference in linear acceleration response between ground surface material for both front- and side-impact sites was found. Helmets with rotational technology resulted in lower rotational acceleration from impacts to the concrete at both impact sites, and mixed gravel surface impacts to the side site. Significantly lower rotational velocity and MPS95 was found with rotational technology present under front impact condition to concrete, and front and side site impacts to mixed gravel.

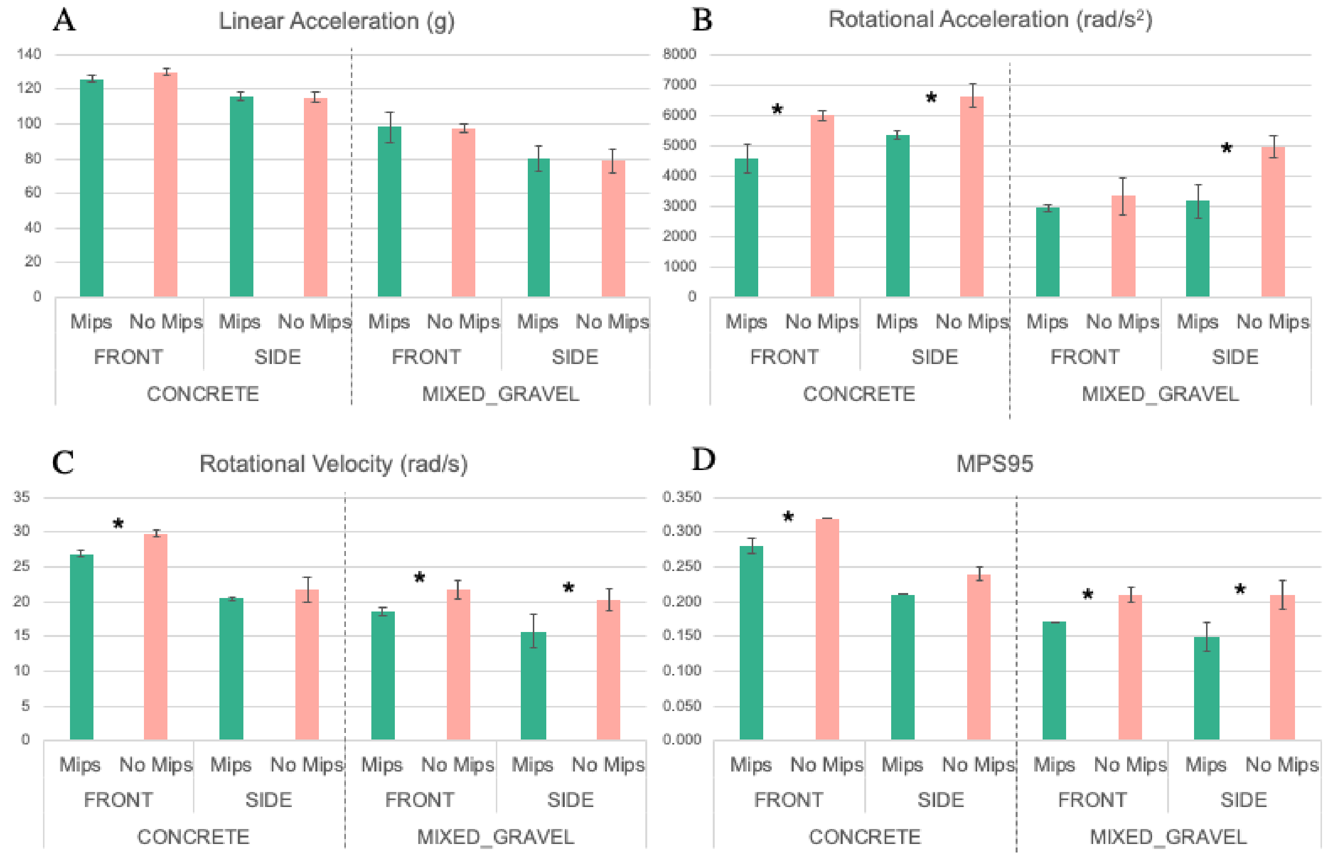

Fig. 7. Peak headform kinematics and brain response resulting from MX helmet with and without Mips, averaged across 3 trials, for impacts to front and side against concrete and mixed gravel: A. linear acceleration, B. rotational acceleration, C. rotational velocity and D. MPS95 for helmets with and without rotational technology.
*denotes a significant difference.

IV. Discussion

This study examined the influence of ground surface materials found within the MX environment on head response during oblique head impacts in Phase A of this study. Although not directly surveyed, the five ground surface materials tested represented a broad range of possible terrain found in MX racing tracks. Impacts in Phase A were performed using a rounded skate helmet to isolate the characteristics of the surface material during head impacts by minimizing variance introduced through helmet geometry. Ground surface materials that resulted in the highest head and brain response, and potential risk of injury [29] were then used to evaluate the performance of an MX helmet with and without rotational mitigating technology in Phase B of this study.

The results from Phase A demonstrated that varied compliant surfaces were identified through peak magnitude head and brain response and duration of the impact (Table III; Fig. 4), resulting from the range in surfaces tested. These finding are similar to previous research findings replicating ground surface conditions that may be like realistic environments [22]. Concrete surface and mixed gravel were found to represent the highest peak head linear and rotational acceleration and MPS95 brain response; dirt represented the lowest head and brain response and longest duration time pulse. With peak linear acceleration of 138.0 g and 98.8 g and peak rotational acceleration of 7330.7 rad/s^2 and 4595.3 rad/s^2 resulting from concrete and mixed gravel, respectively, both surfaces present high probability of concussive outcomes [29]. These results are consistent with previous research examining the influence of surface material and compliance on resulting head response and risk to injury [19-20].

The protective capacity of helmets is commonly evaluated using standard drop equipment, which provides a controlled setting for testing the efficacy of various technologies [14]. This research recreated conditions that could represent real-world characteristics of MX accidents in Phase B of this study, including the impact mechanisms simulating a fall forward at high speeds [23] and two impact materials replicating asphalt and gravel surfaces. The rotational mitigating technology had no influence on resulting head linear accelerations for all impact conditions. This is consistent with previous research, which has shown that rotational management technology has a greater influence on linear accelerations from impacts onto softer compliant surfaces, and less influence from impacts to less compliant surface conditions, such as those replicated in the current study [19].

The presence of the rotational mitigating technology resulted in a significant decrease in both rotational acceleration and velocity, with the level of decrease depending on surface material and impact site. This may have been influenced by a higher variance between impact trials for helmets without rotational technology, where in some cases a larger spread in data were found. For example, the performance of the management system showed less variability for impacts to concrete at the side site and impacts to mixed gravel at the front site, with impacts without rotational technology resulting in higher standard deviations. However, the overall reduction in head rotational components when rotational mitigating technology was present is consistent with research comparing rotational technologies in multiple sports helmets, including motorsport [15-16]. Further, significant differences were reported in brain strain in the current study, matching the same findings in head rotational velocity, suggesting this measurement to be more influential to the tissue properties of the brain model, which is also consistent with previous findings [30].

This research is limited to the properties of the physical and computational models used. These models represent close approximations of human anatomy and physiology but are not considered to be fully biofidelic. The impacts tests in this study were performed without a neck condition, which may have influence on the head response. Although conditioning of each ground surface material was systematic, the properties of the materials, such as dirt and sand, will be more sensitive to the conditioning methods, such as the level of water added and time between impact trials. Further, the materials were contained within a large wooden box which could have influenced the shear properties of the materials and may not fully represent real-world conditions. In addition, it's possible that the material container may have created edge effects during the head impacts. Therefore, our ground surface results are specific to the material conditioning and equipment set-up and may be variable based on what is possible in the MX environment.

V. CONCLUSIONS

Of the five surface conditions tested in the study, concrete and mixed gravel showed the greatest risk to concussive injury through high peak head response variables. Impacts replicating MX accident mechanisms to concrete and mixed gravel surfaces found that MX helmets with rotational mitigating technologies resulted in a significant reduction in head rotational components and brain strain under the tested conditions. Future work should include further development of technologies to improve the efficacy of the rotational mitigating technology under a wider range of surface material conditions and impact velocities as well as boundary conditions such as the inclusion of the rest of the body.

VI. ACKNOWLEDGEMENTS

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Appendix A

TABLE V

HEAD AND BRAIN RESPONSE FOR SKATE HELMETED FRONT SITE IMPACTS TO FIVE SURFACE MATERIALS FOR FIVE IMPACT TRIALS

	Linear Acceleration (g)	Rotational Acceleration (rad/s^2)	Rotational Velocity (rad/s)	MPS95
CONCRETE				
Trial 1	142.2	6725.1	27.7	0.308
Trial 2	139.2	7508.7	28.2	0.313
Trial 3	144.8	7763.3	28.6	0.308
Trial 4	127.0	6860.9	25.7	0.290
Trial 5	136.8	7795.7	27.5	0.296
Ave.	*138.0*	*7330.7*	*27.5*	*0.303*
SD	*6.9*	*505.6*	*1.1*	*0.010*
SAND				
Trial 1	41.5	2239.1	9.7	0.098
Trial 2	54.5	2537.3	9.9	0.098
Trial 3	49.1	2568.5	8.5	0.085
Trial 4	46.4	2120.0	9.9	0.093
Trial 5	43.9	1970.2	9.3	0.089
Ave.	*47.1*	*2287.0*	*9.5*	*0.093*
SD	*5.0*	*261.0*	*0.6*	*0.006*
CRUSHED STONE				
Trial 1	38.4	1802.1	11.0	0.099
Trial 2	43.4	1804.5	9.9	0.084
Trial 3	56.6	1658.3	11.3	0.092
Trial 4	49.3	1542.5	11.0	0.090
Trial 5	62.4	2411.5	14.3	0.124
Ave.	*50.0*	*1843.8*	*11.5*	*0.098*
SD	*9.7*	*335.7*	*1.7*	*0.016*
DIRT				
Trial 1	23.0	914.0	9.8	*0.055*
Trial 2	24.4	843.6	10.7	0.063
Trial 3	24.6	828.7	11.2	0.060
Trial 4	27.3	922.0	11.9	0.066
Trial 5	28.2	810.4	11.3	0.056
Ave.	*25.5*	*863.7*	*11.0*	*0.060*
SD	*2.2*	*51.0*	*0.8*	*0.005*
MIXED-GRAVEL				
Trial 1	103.2	4906.0	21.3	0.233
Trial 2	93.3	4629.7	20.9	0.227
Trial 3	96.5	4768.3	25.4	0.281
Trial 4	106.6	4496.3	23.9	0.264
Trial 5	94.2	4176.0	23.6	0.261
Ave.	*98.8*	*4595.3*	*23.0*	*0.253*
SD	*5.9*	*279.8*	*1.9*	*0.023*

TABLE VI

HEAD AND BRAIN RESPONSE FOR MX HELMETED IMPACTS TO A MIXED-GRAVEL SURFACE FOR THREE IMPACT TRAILS

	Linear Acceleration (g)		Rotational Acceleration (rad/s^2)		Rotational Velocity (rad/s)		MPS95	
FRONT SITE								
	Mips	*No Mips*	*Mips*	*No Mips*	*Mips*	*No Mips*	*Mips*	*No Mips*
Trial 1	88.9	98.8	3009.3	3341.8	19.1	20.6	0.185	0.212
Trial 2	106.6	94.8	2985.7	2716.9	17.8	21.3	0.175	0.207
Trial 3	99.5	98.7	2837.0	3914.0	18.8	23.3	0.180	0.234
Ave.	*98.3*	*97.4*	*2944.0*	*3324.2*	*18.6*	*21.7*	*0.180*	*0.217*
SD	*8.9*	*2.3*	*93.4*	*598.7*	*0.7*	*1.4*	*0.005*	*0.014*
SIDE SITE								
	Linear Acceleration (g)		Rotational Acceleration (rad/s^2)		Rotational Velocity (rad/s)		MPS95	
	Mips	*No Mips*	*Mips*	*No Mips*	*Mips*	*No Mips*	*Mips*	*No Mips*
Trial 1	71.6	73.9	2553.0	4796.2	13.0	19.9	0.118	0.212
Trial 2	84.3	76.2	3314.2	5393.8	17.5	22.1	0.167	0.243
Trial 3	84.2	86.3	3622.6	4711.9	16.7	19.1	1.171	0.197
Ave.	*80.0*	*78.8*	*3163.3*	*4967.3*	*15.7*	*20.4*	*0.150*	*0.210*
SD	*7.3*	*6.6*	*550.5*	*371.8*	*2.4*	*1.6*	*0.020*	*0.020*

TABLE VI

HEAD AND BRAIN RESPONSE FOR MX HELMETED IMPACTS TO A CONCRETE SURFACE FOR THREE IMPACT TRAILS

	Linear Acceleration (g)		Rotational Acceleration (rad/s^2)		Rotational Velocity (rad/s)		MPS95	
FRONT SITE								
	Mips	*No Mips*	*Mips*	*No Mips*	*Mips*	*No Mips*	*Mips*	*No Mips*
Trial 1	124.1	132.0	4090.5	5981.7	26.4	29.6	0.276	0.325
Trial 2	127.0	130.5	4605.1	5849.4	27.3	29.4	0.294	0.323
Trial 3	127.2	127.8	5039.7	6177.0	27.0	30.5	0.299	0.335
Ave.	*126.1*	*130.1*	*4578.4*	*6002.7*	*26.9*	*29.8*	*0.290*	*0.328*
SD	*1.7*	*2.1*	*475.2*	*164.8*	*0.5*	*0.6*	*0.012*	*0.006*
SIDE SITE								
	Linear Acceleration (g)		Rotational Acceleration (rad/s^2)		Rotational Velocity (rad/s)		MPS95	
	Mips	*No Mips*	*Mips*	*No Mips*	*Mips*	*No Mips*	*Mips*	*No Mips*
Trial 1	-	116.6	-	6303.6	-	22.2	-	0.251
Trial 2	114.3	111.8	5461.3	7076.9	20.6	23.2	0.221	0.260
Trial 3	117.5	117.5	5243.4	6537.0	20.3	19.8	0.218	0.231
Ave.	*115.9*	*115.3*	*5352.4*	*6639.2*	*20.5*	*21.7*	*0.210*	*0.240*
SD	*3.2*	*3.1*	*154.1*	*396.6*	*0.2*	*1.7*	*0.000*	*0.010*