Rotational Impact Performance of Bicycle Helmets for Electric Bicycle Riders

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Abstract Electric bicycle (e-bike) riders can experience traumatic brain injury (TBI) in a crash, yet research examining the protection afforded by bicycle helmets for these riders is limited. The objective of this study was to investigate bicycle helmet impact performance in rotational tests reflecting potential e-bike crash conditions. A review of e-bike crash scenarios and travel speeds revealed that rotational impact conditions specified in the ECE R22-06 standard for motorcycle and moped helmets may reflect e-bike head impact conditions. Helmets were fitted to a stocking-covered Hybrid III headform and impacted at R22-06 conditions of 8 m/s onto a 45-degree anvil at five impact locations. Three urban-style bicycle helmet models passing the NTA 8776 bicycle helmet standard for speed-pedelec riders were evaluated: one with no rotation mitigation technology (EPS-only), and two containing rotational technologies. Models with rotational technology significantly reduced all impact kinematics and theoretical TBI risks compared to the EPS-Only model. Rotational kinematics and TBI risks were highest for impacts near the rear of the helmet, although choice of headform was found to affect results considerably. As the NTA 8776 e-bike helmet standard does not include rotational tests, this study can provide helpful reference information for future e-bike helmet standards development.

Keywords Brain injury, Cycling, E-bikes, Head protection, Oblique impact

I. INTRODUCTION

Electric bicycles (e-bikes) are a type of micromobility vehicle similar to conventional pedal bicycles (c-bikes), but with supplemental power provided by an onboard battery. Motorised assistance is generally supplied to one of two levels depending on the classification of the e-bike. In Europe, pedal assist e-bikes provide assistance up to 25 kph (termed 'pedelecs') or 45 kph (termed 'speed-pedelecs' or 's-pedelecs'). These limits are similar in the United States (US), with assistance up to 32 kph or 45 kph. Throttle assist, in addition to pedal assist, is also an option for some e-bike classes, with similar speed-based assistance limits.

E-bikes have seen a dramatic increase in popularity worldwide over the past 20 years [1-6]. The momentum is expected to continue, with the e-bike market projected to grow from $25 billion in 2020 to $48 billion in 2028 [7]. The popularity of e-bikes is a testament to the many benefits they can provide; e-bikes are a cost effective transport method [3][8], they are considered more environmentally friendly than automobiles [2-3][8], they enable riders to travel longer distances or at faster speeds for the same c-bike effort level [2-3], and they lower the physical fitness barrier to cycling for many [3]. City e-bike ride-share programs are responsible for large increases in ridership as well [3].

Parallel to the increase in e-bike popularity has been a corresponding increase in e-bike related injuries [2-3][8-9]. In the US alone, e-bike related injuries increased by approximately 300% from 2019 to 2023 [8]. Head injuries are a leading cause of severe morbidity and mortality in bicycle-related crashes [6], and the head is one of the most commonly injured body regions in e-bike crashes [4][8-9]. Traumatic brain injuries (TBIs) are a frequent diagnosis and can range from mild to severe [1][4-5]. TBI rates and severity levels resulting from e-bike crashes have been shown to be similar to or greater than those resulting from c-bike crashes [1][5-6][8-10]. Regardless of bicycle type (e-bike or c-bike), higher speeds have been associated with higher risk of TBI [6].

Although bicycle helmets have been found to be effective in reducing head injury risks for c-bike riders through both epidemiological and biomechanical studies [11-14], their effectiveness in e-bike crashes has not been as thoroughly studied. Reference [1] showed that helmets reduced risk of skull fracture for e-bike riders, but reduction in risks of other head injuries did not reach significance, while [10] found that helmets reduced the

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occurrence of brain bleeds and overall TBI severity. No detail was provided on the types of helmets worn in either study. At present, the only safety standard specifically covering bicycle helmets for e-bike riders is NTA 8776 – a Dutch national standard that is used as a technical specification in several other countries as well [15]. NTA 8776 pertains specifically to s-pedelec riders. It closely follows the European safety standard for bicycle helmets (EN1078 [16]), but with an expanded coverage area and higher impact speeds (up to 6.5 m/s vs 5.4 m/s). The impact attenuation portion of NTA 8776 comprises of vertical drop tests of a helmeted headform at a perpendicular angle to the impact anvil, producing predominantly linear impact forces. Headform linear acceleration must be limited to below 250 g for the helmet to pass.

While NTA 8776 ensures linear impact forces are managed during a head impact, research has indicated that cyclist head impacts most commonly occur at an oblique angle, inducing rotational forces as well as linear [17-20]. The addition of rotational forces has clinical significance, as rotational motion of the head is a key mechanism in producing various types of TBI [21-23]. Given this clinical significance, rotational testing (i.e. oblique impact tests measuring both linear and rotational head kinematics) is starting to be incorporated into bicycle and motorcycle helmet test standards [24-25]. However, to-date there are no required rotational tests for bicycle helmets for e-bike riders, and the ability of bicycle helmets to mitigate rotational impacts in e-bike-relevant crash scenarios has largely been unexplored. The objective of this study was to therefore investigate the performance of bicycle helmets for e-bike riders in rotational impact tests representative of potential e-bike crash conditions.

II. METHODS

Head Impact Conditions in E-Bike Crashes

To gain an understanding of head impact conditions relevant in e-bike crashes, published studies evaluating e-bike rider crash scenarios were reviewed. Numerous studies have reported that single cyclist crashes are two-to-three times more common than collisions with motor vehicles, other cyclists, or pedestrians for producing e-bike rider injuries [1][4-5][9][26-27]. Common causes of single cyclists crashes include losing balance (often due to slow speeds combined with heavier bikes) [7][9][26-29], obstacles or evasive manoeuvring [4][27-29], unfamiliarity with the bike [7][28-29], travelling too fast for the conditions [4][27-28], alcohol [4][28], distraction [28], and technical problems with the bike [28]. Those travelling at fast speeds (i.e. >25 kph) were more likely to sustain serious injuries [6][26][28], although many injuries were found to occur at lower speeds as well, including speeds <5 kph [9][26][28]. In light of these findings, single cyclist crash conditions were the focus of the present testing.

Published studies measuring e-bike travel speeds were also considered for determination of appropriate e-bike head impact conditions (Table I). Only studies that filtered out stoppage time or provided free-flow cruising speeds were included to avoid underestimation of travel speeds. Generally, these studies were set in urban areas in Europe, with some rural trips included as well. Overall, pedelec speeds averaged around 20 kph, with maximum speeds reaching the 25 kph assistance limit or slightly above [30-34]. S-pedelec speeds averaged around 30 kph, with maximum speeds reaching up to 40 kph [30-31][35-36]. Notably, s-pedelec riders did not often reach the 45 kph assistance limit. This was attributed to the considerable effort required to maintain this top speed [35-36]. Pedelec and s-pedelec rider average speeds were found to be 2-4 kph [7][30-32][34] and 9-13 kph [30-31] greater than c-bike rider average speeds, respectively.

To translate e-bike crash scenarios and travel speeds to head impact conditions for helmet testing, a relevant computational simulation study was relied upon [37]. Physics-based full body simulations allow for the body's interactions with the bicycle and surrounding environment during a crash to be estimated, possibly facilitating improved approximations of head impact conditions. Reference [37] used multibody modelling to simulate single cyclist crashes at travel speeds of 5.5 m/s (20 kph) and 11.1 m/s (40 kph), which align with average pedelec and upper s-pedelec travel speeds. Simulations spanned a range of single cyclist fall trajectories. The authors found an average resultant head impact velocity of 6.7±1.1 m/s at 35±8 deg from vertical for the 5.5 m/s travel speeds and an average resultant head impact velocity of 10.2±2.0 m/s at 57±6 deg from vertical for the 11.1 m/s travel speeds. The normal component of the head impact velocities (4.8-6.2 m/s) were in the realm of linear impact speeds specified in present safety standards [15-16] and did not vary much with increasing travel speed, while the tangential component of the head impact velocities increased dramatically across travel speed (3.7±0.9 m/s for 5.5 m/s speeds vs 8.6±1.7 m/s for 11.1 m/s speeds).

TABLE I
E-BIKE TRAVEL SPEEDS REPORTED IN PUBLISHED SCIENTIFIC LITERATURE. ALL STUDIES ARE NATURALISTIC AND RELIED ON INSTRUMENTED E-BIKES TO COLLECT MEASUREMENTS.

E-Bike Type	Study	Methodological Notes	Metric	Speed [kph]
25 kph Pedelec	Schleinitz *et al.*, 2017 [31]	- 85 participants (ages: 31% ≤40 years, 34% 41-64 years, 35% ≥65 years) - 28 c-bikes, 48 pedelecs, 9 s-pedelecs (no s-pedelec riders ≥65 years) - All road/path types around Chemnitz, Germany - 0 kph data removed	Mean Free Flow	19
			Max Free Flow	33
32 kph Pedelec	Langford *et al.*, 2015 [32]	- 100 participants in a university setting (ages: 82% students ≤21 years, 18% faculty and staff) - 6 ride-share c-bikes, 7 ride-share pedelecs - Ride-share users in urban areas around Knoxville, US - Speeds <2 kph removed	85th %ile Overall Trip	20
			99th %ile Overall Trip	32
25 kph Pedelec	Twisk *et al.*, 2021 [30]	- 46 participants (ages: 25-56 years, average 43.7 years) - 14 c-bikes, 12 pedelecs, 20 s-pedelecs - Commuters around the Hague, Netherlands - Speeds <5 kph removed	Mean Overall Trip	21
25 kph pedal assist / throttle	Dozza *et al.*, 2016 [34]	- 12 participants (ages: 22-50 years, average 37.6 years) - All 25 kph e-bikes - All road/path types around Gothenburg, Sweden - Stops >2 min removed	Mean Overall Trip	17
			Fastest Rider Mean Overall Trip	21
S-pedelec	Schleinitz *et al.*, 2017 [31]	- 85 participants (ages: 31% ≤40 years, 34% 41-64 years, 35% ≥65 years) - 28 c-bikes, 48 pedelecs, 9 s-pedelecs (no s-pedelec riders ≥65 years) - All road/path types around Chemnitz, Germany - 0 kph data removed	Mean Free Flow	25
			Max Free Flow	34
S-pedelec	Stelling *et al.*, 2021 [36]	- 28 participants (ages: 26-56, average 44.9 years) - All 45 kph s-pedelecs - Commuters in urban areas around Netherlands - Speeds <1 kph removed	Mean 50 kph roads	32
S-pedelec	Twisk *et al.*, 2021 [30]	- 46 participants (ages: 25-56 years, average 43.7 years) - 14 c-bikes, 12 pedelecs, 20 s-pedelecs - Commuters around the Hague, Netherlands - Speeds <5 kph removed	Mean Overall Trip	29
S-pedelec	Herteleer *et al.*, 2022 [35]	- 98 participants (ages: 23-59 years, average 41.4 years) - All 45 kph s-pedelecs - Commuting and leisure around Flanders, Belgium - Cruising speed/max speed calculations excluded stoppage time	95th %ile Overall Trip	40
			Mean Cruising Speed	36

E-bike Helmet Testing

Based on the findings of [37], head impact speeds between 6.7-10.2 m/s at angles of 35-57 deg were targeted for the present testing. Notably, the rotational test conditions of 8 m/s at 45 deg specified in the ECE R22-06 European standard for motorcycle and moped helmets fall central to this range and consequently may be relevant for e-bike riders [25]. S-pedelecs are classified as mopeds in Europe, and several European countries therefore require riders to wear motorcycle or moped helmets meeting the R22-06 standard [38]; however, according to the authors' knowledge, the performance of bicycle helmets for e-bike riders in R22-06 test conditions has yet to be reported on. An impact speed of 8 m/s onto a 45 deg angled anvil was thus selected for the present testing. The anvil was covered with 80-grit sandpaper to simulate road surface friction (Fig. 1) [25] and was replaced after every three impacts.

Reference [37] reported head impact locations covering most of a typical bicycle helmet coverage area, with the majority of impacts concentrated at the front and sides and the fewest impacts at the rear. R22-06 specifies impact locations around the entire helmet, including front, front lateral right, lateral left, rear, and rear lateral right locations [25]. Although results from [37] may indicate that R22-06 impact locations around the rear are less common for e-bike riders, more in-depth e-bike accident reconstruction data are needed to improve confidence in the distributions of impact locations for e-bike riders. All R22-06 locations were thus evaluated in the present testing (Fig. 1). Per R22-06, one helmet sample was subjected to impacts at the front lateral right, rear, and lateral left locations, while another helmet sample was subjected to impacts at the front and rear lateral right locations. Each helmet sample was impacted only once per location. Three replicates were conducted per impact location, for a total of 15 impacts across 6 samples per helmet model.

Three urban-style bicycle helmet models passing the NTA 8776 bicycle helmet standard for high-speed e-bike riders were evaluated. One model did not contain any technology specifically targeting reduction of rotational kinematics (termed 'EPS-Only' to reflect the expanded polystyrene (EPS) liner), while the other two models contained rotational technologies found in the bicycle helmet market (Tech 1 and Tech 2). These commercially available helmets contained notable similarities in overall shape, comprising of a smooth, rounded exterior with minimal venting. Tech 1 and Tech 2 helmets both were given a 5-star rating by the Virginia Tech Helmet Ratings [39], suggesting that both helmets reduce head kinematics reasonably well in c-bike impact conditions. Tech 1 relies on a sliding mechanism at the head-helmet interface to divert rotational energy, while Tech 2 relies on a combination of sliding and shearing at the head-helmet interface.

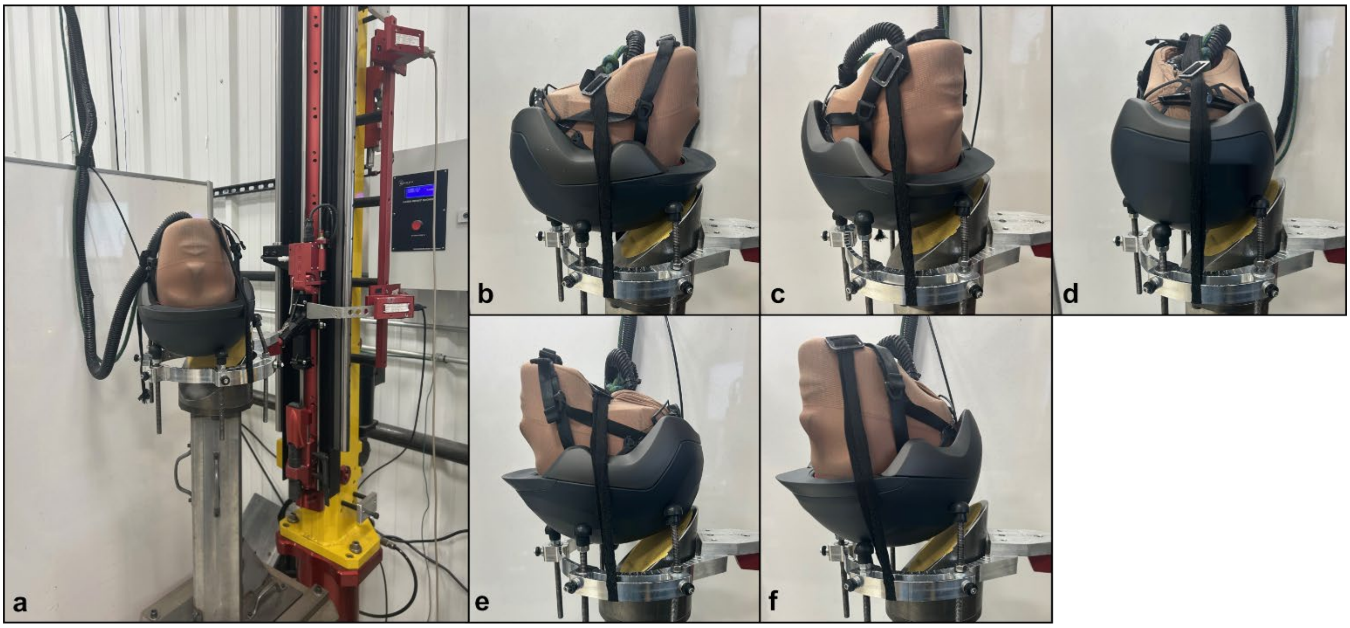

Fig. 1. a) Rotational test setup. A support ring with rods was used to position the helmeted headform and hold it in place during the drop. Upon impact, the support ring passed around the angled anvil, allowing the helmeted headform to move independently. An elastic strap secured by an electromagnet prevented the helmeted headform from shifting during the drop and was released shortly before impact. A flag attached to the drop mass passed through a light gate just prior to impact to record the impact speed. Impact locations were set using an inertial measurement unit (LPMS-B2, LP-Research, Tokyo, Japan), and include b) front (0 deg), c) front lateral right (45 deg rotation about headform Z axis), d) lateral left (270 deg rotation about headform Z axis), e) rear (180 deg rotational about headform Z axis), and f) rear lateral right (135 deg rotation about headform Z axis).

The primary difference in test setup between R22-06 and the present study was the headform selected for testing. A 50th percentile male Hybrid III (HIII) headform, covered with two nylon stockings, was used instead of the EN960 headform used in R22-06 testing [25]. This decision was made owing to recent research indicating that a stocking-covered HIII reflects human head inertial and surface friction properties more closely than the EN960 headform [40-43], and that the EN960 headform properties tend to underestimate head rotational kinematics in rotational testing [42-43]. The nylon stockings were inspected between tests and replaced if tears or stretches were observed. 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). Helmets were fitted to the headform by adjusting the retention dial and tightening the chin straps under the chin in accordance with manufacturer guidelines, with the tester able to fit one finger width between the strap and the chin. The brow of the helmet was positioned approximately 1 inch above the brow line.

Data were sampled at 20 kHz during each test (SLICE MICRO, DTS, Seal Beach, CA, USA). Linear acceleration data were filtered according to SAE J211 using channel frequency class (CFC) 1000 [44], while rotational velocity data were filtered at CFC 180 [45]. Rotational velocity curves were differentiated to produce rotational acceleration data using a central difference algorithm [45]. Resultant peak linear acceleration (PLA), peak rotational velocity (PRV), and peak rotational acceleration (PRA) were determined per test. In addition, as TBI is a common injury diagnosis following e-bike crashes [1][4-5], Brain Injury Criteria (BrIC) was also calculated and used to determine the theoretical risk of Abbreviated Injury Scale 2 and 5 (P(AIS2) and P(AIS5)) brain injury for each impact [46]. BrIC was specifically selected owing to its use in the R22-06 standard [25]. AIS2 and AIS5 severities were chosen to represent the most common TBI severity reported for e-bike riders and a much more severe TBI level that may sometimes be observed for e-bike riders, respectively [1][4-6][10]. Equations 1-3 show the respective calculations for BrIC, P(AIS2), and P(AIS5), where $\omega_{x/y/z}$ are PRV in the x-, y-, or z-directions, and $\omega_{xC/yC/zC}$ are critical PRV values. The influence of impact location and helmet model on results were investigated using two-way ANOVA with Tukey's HSD post hoc tests.

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

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

$$P(AIS5) = 1 - e^{-\left(\frac{BrIC}{1.252}\right)^{2.84}} \quad (3)$$

III. RESULTS

Impact speeds for all tests averaged 8.01 ± 0.06 m/s. Across each helmet model and location, average PLA, PRA, and PRV ranged from 133-172 g, 3,742-13,455 rad/s^2, and 23-54 rad/s, respectively (Fig. 2-4). Compared to the EPS-Only model, models with rotational technology reduced PLA by 12 g on average (7%, p<0.01), PRA by 3,122 rad/s^2 on average (34%, p<0.01), and PRV by 10 rad/s on average (24%, p<0.01). PRA and PRV across Tech 1 and Tech 2 were also significantly different on average (PRA difference: 1,025 rad/s^2, p<0.01; PRV difference: 3.1 rad/s, p<0.01). However, these differences were smaller than the differences between EPS-Only and rotational technologies, and PRV and PRA did not differ significantly between Tech 1 and Tech 2 at all locations (i.e. p>0.73 at lateral left and rear lateral right). PLA did not differ significantly between the two technologies (p=0.09). Comparing across impact locations, the rear lateral right location produced significantly lower PLAs than the other locations (16 g lower on average, p<0.01), while the rear and rear lateral right locations both produced significantly higher PRA and PRV compared to all other locations (Rear: 16 rad/s and 4,374 rad/s higher on average, p<0.01; Rear lateral right: 9 rad/s and 2,619 rad/s^2 higher on average, p<0.01). Although the present testing used a different headform than R22-06, it is notable that the R22-06 PRA pass-fail threshold of 10,400 rad/s^2 [25] was exceeded by the EPS-Only helmet at the rear and rear lateral right locations and by the Tech 1 helmet at the rear location.

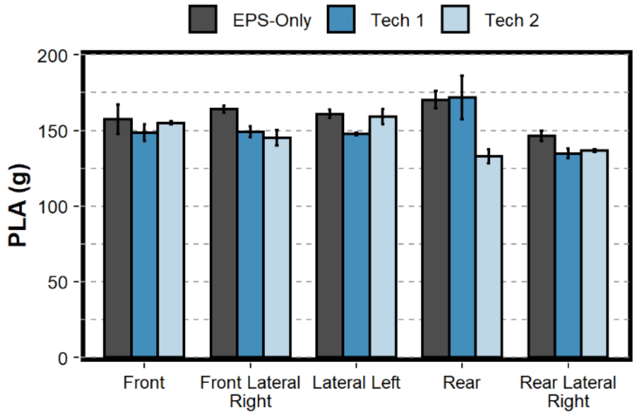

Fig. 2. PLA results for all helmet models and locations.

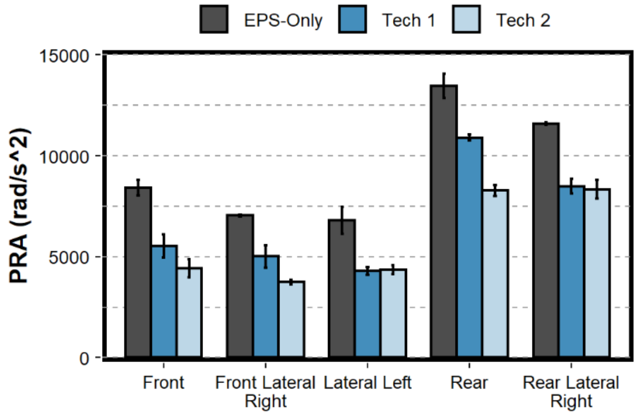

Fig. 3. PRA results for all helmet models and locations.

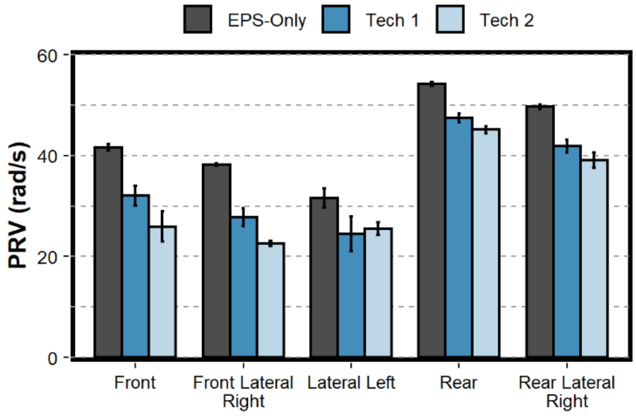

Fig. 4. PRV results for all helmet models and locations.

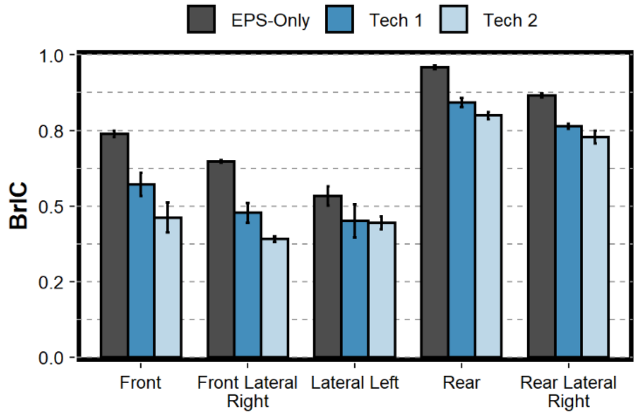

Fig. 5. BrIC results for all helmet models and locations.

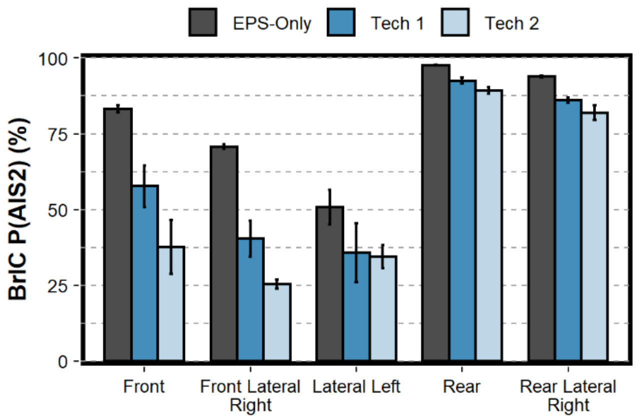

Fig. 6. Theoretical AIS2 brain injury risk results for all helmet models and locations.

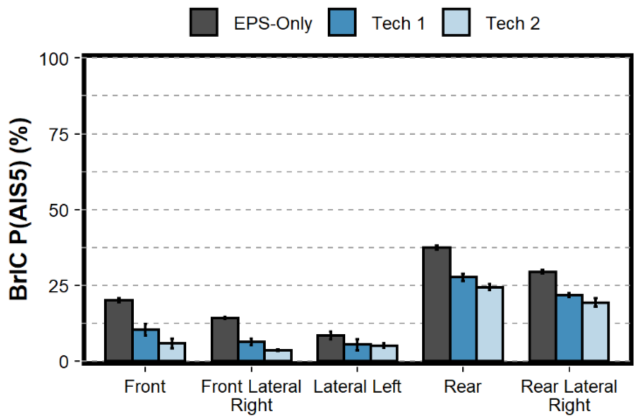

Fig. 7. Theoretical AIS5 brain injury risk results for all helmet models and locations.

Trends in BrIC and BrIC-based injury risks reflected trends in rotational kinematics. Average BrIC values ranged from 0.39-0.96 across all helmet models and locations (Fig. 5), producing average theoretical AIS2 and AIS5 brain injury risks that spanned from 25-98% and 4-37%, respectively (Fig. 6-7). Models with rotational technology produced significantly lower BrIC values than the EPS-Only model (22% lower, $p<0.01$), translating to an average reduction in theoretical injury risk of 21% for AIS2 (29% lower, $p<0.01$) and 9% for AIS5 (45% lower, $p<0.01$). Average differences in BrIC and theoretical injury risks across Tech 1 and Tech 2 also were significant (BrIC difference: 0.06, $p<0.01$; P(AIS2) difference: 8.7%, $p<0.01$; P(AIS5) difference: 2.7%, $p<0.01$), although smaller than the differences between EPS-Only and rotational technologies. BrIC values and associated theoretical injury risks were also significantly higher at the rear and rear lateral right locations (Rear: BrIC 0.28, P(AIS2) 35%, and P(AIS5) 17% higher on average, $p<0.01$; Rear lateral right: BrIC 0.18, P(AIS2) 28%, and P(AIS5) 10% higher on average, $p<0.01$). Again, although the present testing used a different headform than R22-06, it is notable that

BrIC values exceeded the R22-06 pass-fail threshold of 0.78 for all helmet models at the rear location and the EPS-Only helmet at the rear lateral right location [25].

IV. DISCUSSION

Helmet rotational impact testing can assist in evaluation of head injury risk for e-bike riders. Three urban style bicycle helmets meeting the NTA 8776 standard for helmets for s-pedelec riders were evaluated under impact conditions potentially relevant to e-bike crash conditions. The impact speed evaluated was higher than prescribed testing for bicycle helmets currently [15-16][24], matching motorcycle and moped helmet standards [25]. Despite the high energy of these impacts, no helmet model experienced EPS densification leading to extreme impact forces (i.e. 'bottoming out'), as evidenced by the relatively low PLA results. For all tests, PLA was kept below 200 g, which is well below the NTA and EN1078 standard pass-fail requirement of 250 g. As PLA and normal velocity have been shown to be correlated [47], and as the normal component of the impact speed in the present testing was in the realm of current bicycle helmet standards at 5.7 m/s [15-16], the fact that these certified helmets produced PLAs below 250 g is to be expected.

The rotational technologies evaluated were found to be effective in reducing rotational kinematics and theoretical brain injury risks compared to the EPS-only model despite the high impact speeds evaluated. While some significant differences in rotational kinematics and injury risks were identified between Tech 1 and Tech 2, it cannot be generalised from this data that one technology provides superior impact protection for e-bike riders owing to the fact that only one model per technology was tested. Previous studies have demonstrated that rotational technology performance varies across helmet model [48-49]. It is likely that differences between Tech 1 and Tech 2 varied across location due to slight differences in external helmet shape and nuances in the interaction between the technologies and the headform and helmet interior. The significant reduction in theoretical risks of both mild (AIS2) and more severe (AIS5) TBI afforded by both rotational technologies in the current results is meaningful, as several studies have found that mild TBI is common for e-bike riders involved in crashes [1][4-5], while some have determined that TBI severity is often greater for e-bike riders than c-bike riders [1][5][10]. It should be noted that many of the more severely injured riders in these studies were unhelmeted [1][10]. In the present study, all helmets, including the EPS-Only helmet, kept AIS5 theoretical injury risks relatively low (<40% for all impacts). Although an unhelmeted scenario was not tested due to the risk of damaging the test equipment, it is highly likely that TBI risks would be considerably greater in unhelmeted scenarios [10][13-14]. This highlights the importance of encouraging helmet use for e-bike riders.

As the present test method reflected the rotational test conditions of the R22-06 standard for motorcycle and moped helmets, it is especially interesting to consider how the present NTA 8776 certified bicycle helmet results might compare to R22-06 certified motorcycle or moped helmet results. A recent study evaluating the rotational impact performance of R22-06 certified motorcycle helmets in similar impact conditions to those evaluated herein enables an approximate comparison [50]. The authors used a HIII headform and 45-degree anvil to impact the motorcycle helmets at a variety of locations, including front and lateral locations matching the present study. The primary differences in the test methodology of [50] were that the HIII was not covered with stockings and a lower grit sandpaper was used, both of which affect friction interfaces in an impact and may influence rotational results. Nonetheless, outside of a slightly higher PLA at the front location and a slightly lower PRA at the side location, the PLA, PRV, PRA, and BrIC results from the present study were within one standard deviation of the average R22-06 motorcycle helmet results. These similarities suggest that NTA 8776 certified bicycle helmets and R22-06-certified motorcycle helmets may provide comparable rotational impact protection in conditions potentially relevant for e-bike riders. However, more testing with the exact same friction interfaces is needed to confirm this finding.

In the current study, rotational kinematics and injury risks were highest near the rear of the helmet, with theoretical AIS2 injury risks averaging around 90% at these locations and some impacts exceeding the R22-06 proposed PRA and BrIC thresholds. Although the simulation study used to inform the present testing suggests that impacts around the rear of the helmet may not be as common for single cyclist crashes as locations around the front and sides [37], more in-depth e-bike accident reconstruction data are needed to improve confidence in the distributions of impact locations for e-bike riders. The higher results at the rear locations are likely in part due to the effect of headform orientation on impact dynamics; at locations near the rear of the helmet, the distance from the impact location to the headform CG is longer, resulting in a larger moment arm than other impact locations. It is also important to note that the HIII headform used in this testing has been shown to produce considerably higher rotational kinematics than the EN960 headform used for R22-06 testing [42-43]. Specifically, in helmeted sagittal plane impacts around 7 m/s, the HIII headform produced PRAs that were approximately 4,000-8,000 rad/s^2 greater than the EN960 headform [42-43]. To investigate further, we conducted several additional tests at the rear and rear lateral right locations using the EN960 size J headform for all three helmet models evaluated herein. For the EN960 headform, PRA was reduced by 5,999 rad/s^2 and BrIC was reduced by 0.45 on average, demonstrating that none of the helmet models would have exceeded the R22-06 pass-fail thresholds when using the EN960 headform.

Comparing the present results using the HIII and EN960 headforms to the R22-06 pass-fail threshold highlights the considerable implications that headform selection has on helmet rotational impact performance. The drastic differences in results suggest that standards' pass-fail thresholds need to be interpreted with specific headforms in mind. Recent studies have highlighted that headform surface friction and moments of inertia (MOIs) directly affect impact results during rotational testing of helmets [42-43][51-52]. The EN960 headform has been shown to have higher MOIs and possibly lower surface friction compared to the human head [40][42-43], resulting in lower rotational kinematics and theoretical injury risks than other headforms [42-43]. This aligns with the current findings. On the other hand, a study on rotational testing of the HIII headform found that covering the headform with nylon stockings (as was done in the present testing) lowered the surface friction coefficient down from an unrealistically high level to a level more aligned with human head friction properties, and that this reduction in surface friction produced significantly lower rotational kinematics during impact testing [41]. While inertial properties of the HIII are generally closer to that of the human head than the EN960 [42-43], its MOIs in some directions are still slightly lower than those predicted for a human head of the same circumference. This indicates that a stocking-covered HIII may still overestimate rotational head kinematics for a given test. To address the shortcomings of existing headforms in replicating human properties relevant for rotational impact tests, Working Group 11 in Europe recently spearheaded the development of new headform specifications for rotational testing that reflect human properties more accurately [24]. If rotational tests were to be added to e-bike helmet standards in the future, it would therefore be prudent to consider adopting headforms that meet these new specifications and determining pass-fail thresholds accordingly.

The evaluation of rotational kinematics in helmet impact testing can provide a basis for evaluating TBI risk – an injury which epidemiological studies have shown is relevant for e-bike riders [1][4-5] – and therefore may be desirable to incorporate into future versions of e-bike helmet standards. While NTA 8776 ensures that helmets for e-bike riders can manage higher linear impact forces than other current bicycle helmet standards [15], this study evaluated rotational performance of such helmets in conditions that may be particularly relevant to e-bike riders. Notably, after reviewing numerous studies on e-bike crash scenarios and travel speeds and using a relevant simulation study to translate this information into estimated head impact conditions, the rotational test conditions of the R22-06 standard for motorcycle and moped helmets were found to align very well with potential head impact conditions for e-bike riders. This finding may be useful for future e-bike helmet standards development. More research is needed on the appropriateness of other elements of the R22-06 standard for e-bike riders, however. R22-06 contains many other differences in testing compared to current bicycle helmet standards tests, including much higher linear impact speeds (up to 8.2 m/s), crushing tests, tests for surface projections, and more [25]. Current R22-06 helmets may be considered restrictive in terms of weight and, especially, breathability by riders of pedelec and s-pedelec bicycles, for whom considerable physical exertion is still required compared to riders of mopeds or motorcycles [15].

There are several limitations associated with the current work. Head impact conditions during e-bike rider crashes were estimated by reviewing current literature and cross referencing with a computational simulation study. More in-depth e-bike accident reconstruction efforts are needed to improve confidence in e-bike rider head impact conditions. This work also did not consider head impact conditions from collisions with motor vehicles, which should be investigated further. One limitation pertaining to the R22-06 test conditions used herein is that no impact location is specified that induces primarily transverse plane rotation, which the brain is thought to be sensitive to [46]. Additionally, while the 8 m/s impact speed represents a possible head impact speed that could be attained by either pedelec or s-pedelec riders, [37] found head impact speeds of 10.2±2.0 m/s for riders travelling at 40 kph [37], and s-pedelec riders can sometimes reach speeds higher still [36]. Future research should investigate the effectiveness of bicycle helmets at these top speeds. Another limitation related to relying on [37] in the present research is that the authors modelled a c-bike rather than an e-bike. While some have suggested that the body decouples from the bike early during a crash [53], the additional mass of an e-bike may affect simulation results. In addition, as only three helmet models were investigated presently, more NTA 8776-approved bicycle helmets should be evaluated to make the findings more generalisable. The use of BrIC to estimate TBI risk also has associated limitations, as some have suggested that it may overpredict injury likelihood [54]. Lastly, many studies have shown that e-bike riders tend to be older on average than c-bike riders [1-2][5-6][9-10], and it is thought that older populations are more susceptible to TBI than younger populations [1][6][10]. Future work should specifically evaluate bicycle helmet appropriateness for older e-bike riders.

V. CONCLUSION

This study offers insights into the rotational impact performance of current bicycle helmets for e-bike riders, an area which has been largely unexplored previously despite the possible TBI risk for these riders. Rotational head impact conditions relevant in e-bike crashes were approximated by reviewing studies on e-bike crash scenarios and travel speeds and cross-referencing with computational simulation research. The high impact speed selected for this study reflected speeds that e-bike riders may be capable of and matched motorcycle and moped helmet standards. Despite this high impact energy, no helmet model experienced bottoming out, and the rotational technologies evaluated were still effective in reducing head kinematics and brain injury risks compared to the EPS-only model. Results also highlighted the importance of headform selection on rotational pass-fail criteria in standards. As the NTA 8776 e-bike helmet standard does not include rotational impact tests, this study can provide helpful reference information for future e-bike helmet standards development.

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