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Advanced Cycle Helmet Testing Protocols: Effects of Linear Impact Energy and Compound Impacts on Cycle Helmet Safety

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1 Introduction

Cycling is increasing in its popularity, both as a mode of transport and as a recreational activity, with approximately 6.5 million adults across Great Britain (GB) cycling at least once a month and travelling an estimated 5.6 billion vehicle kilometres (bvkm) on the road (DfT, 2016; DfT, 2017a). Cyclists are a particularly vulnerable road user (VRU) group, however, with a casualty rate of 3,327 casualties per bvkm; the second highest rate in GB (DfT, 2017b). In total, 3,499 cyclists were either killed or seriously injured in 2015 alone.

Traumatic brain injuries pose the greatest risk of fatal and serious injuries to cyclists and are typically associated with around one-third of cyclist hospital admissions and three-quarters of cyclist fatalities (Thompson *et al.*, 2000; Macpherson A, 2008; Olivier and Creighton, 2016). The use of helmets when cycling is a risk management practice that intends to provide additional protection to a wearer in the event of a fall or if struck by an object. The principal purpose of a cycle helmet is to protect the head from blunt impacts that would otherwise impart large forces and accelerations to the head and cause traumatic brain injuries (Hynd *et al.*, 2009).

It has widely been recognised that, despite being a critical item of personal protective equipment, the safety performance of cycle helmets can vary considerably between models (Stigson and Kullgren, 2015; DeMarco *et al.*, 2016; Stigson, 2017). Currently, no independent and freely available information is provided to consumers at the point of sale to support them with assessing the safety performance of cycle helmets. This is in stark contrast to motorcycle helmets, where safety performance ratings are provided to consumers through the SHARP helmet testing and assessment protocols (Delmonte *et al.*, 2015).

One key reason for this paucity of information is a need to understand the fundamental science underpinning the development of such protocols for cycle helmets. The effects of impact energy, impact partner shape and compound impacts (where a single location on the helmet is impacted multiple times) on the degradation of helmet safety performance are not well characterised by the literature. Whilst greater head impact energies have been observed to result in worse outcomes, there is limited evidence to suggest what effect impact partner shape has on the outcome (DeMarco *et al.*, 2016; Cripton *et al.*, 2014; Sahoo *et al.*, 2015). Likewise, if a cycle helmet is impacted multiple times in the same location (e.g. if a cyclist strikes the A-pillar of a car, before striking the ground), the effect of helmet damage and impact shape remain unknown.

This novel research study therefore aims to quantify the effects of impact energy and compound impacts, for both flat and kerbstone impact anvil designs, on the risks of head injury for a single helmet model.

2 Methods

2.1 Ethics

No ethical approval was required for this experimental study, as no human subjects were recruited for participation.

2.2 Cycle Helmets

To ensure suitable control of the mechanical characteristics of the cycle helmets, only one model, a size medium (54-59 cm) Trax Mistral Bike Helmet, was selected for testing in this study.

2.3 Helmet Testing Standards and Protocols

The experimental procedures adopted by this study were based on the following helmet testing standards and protocols:

- Snell B-95. 1995 Standard for protective headgear: 1998 revision (Snell Memorial Foundation, 1998).
- EN 1078:2012+A1:2012. Helmets for pedal cyclists and for users of skateboards and roller skates (BSI, 2012).

The Snell B-95 bicycle helmet standards establish the performance characteristics of the helmets by performing wire-guided drop tests of helmeted hemispherical headforms to assess the effects of linear impacts. Helmeted headforms are dropped from heights of 2.24 m and 1.42 m onto flat and hemispherical/kerbstone anvils. Helmets are considered to be safe if the linear accelerations experienced by the headform remain below 300 *g*.

European Standard EN 1078:2012+A1:2012 performs falling headform drop tests onto a flat anvil to assess the impact absorption performance of cycle helmets within a specified testing area. Helmeted headforms are dropped from heights of 1.50 m and 1.06 m onto flat and kerbstone anvils. Helmets are considered to be safe if the linear accelerations experienced by the headform remain below 250 *g*.

2.4 Head Injury Thresholds

Aside from the previously described performance criteria requirements in existing helmet testing standards, several established head injury thresholds were further used within this research. When considering linear head accelerations, Newman (1980) established a scale relating linear acceleration thresholds to Abbreviated Injury Scale (AIS) scores (Newman, 1980). Newman (1980) concluded that peak linear head accelerations of >250 *g* are associated with an AIS5+ head injury severity, whilst peak accelerations of >100 *g* correlate with an AIS2+ severity.

2.5 Drop Test Assembly

A wire guided drop test assembly consisting of a ball-arm, headform mount collar and carriage, and compliant with Snell B-95 requirements, was used for all drop tests (Snell Memorial Foundation, 1998). This approach was selected to give a more repeatable experimental procedure and as it controls for headform rotations during the wire guided drop tests.

2.6 Headform

All drop tests used an instrumented EN 960:2006 compliant 575 mm circumference half headform (5 kg combined mass for headform and drop test assembly).

2.7 Impact Anvils

Helmeted headforms were drop tested onto EN 1078:2012+A1:2012 compliant flat and kerbstone shaped impact anvils according to the appropriate testing procedure.

2.8 Impact Test Locations

Two impact test locations, within the left and right temporal regions of the helmet were used in this study (Figure 1). These were specified at the intersections of the coronal plane and test region boundary specified within EN 1078:2012+A1:2012 requirements. Impact locations were marked for testing using a certified laser alignment table.

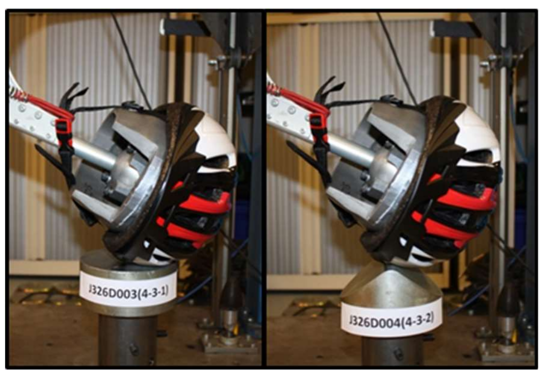

Figure 1: Wire guided linear headform drop test set-up for the impacting the right temporal region on flat and kerbstone anvils

2.9 Headform Positioning

All helmeted headforms were positioned to ensure the linear impact forces acted through the impact location and the centre of gravity of the helmeted headform and drop test assembly.

2.10 Sample Preparation

Fifteen medium sized helmets (to fit the EN 960:2006 575 mm circumference headform) were tested in this study. All helmets were tested in the condition they were offered for sale, including shell apertures, accessory attachments and comfort padding, with no pre-conditioning performed.

2.11 Testing Procedures

Each helmeted headform was impacted four times, with two consecutive drops of each cycle helmet performed at each impact location. The first drop was performed for heights ranging from 1-3 m, in 0.5 m increments, whilst the second drop was performed from a drop height of 1 m only. Helmets were either dropped onto the flat or kerbstone shaped anvil using a design of experiments approach (see test matrix summarised in Appendix A). This ensured that three tests were performed for each investigated variable and that the number of helmets purchased was minimised.

To perform these tests, each helmet was mounted and securely fastened via its restraint system to the headform, before positioning the helmeted headform for testing at the impact location. Each helmeted headform and drop test assembly was then raised to their specific drop height, before being dropped onto the anvil.

2.12 Data Processing

The linear accelerations experienced at the centre of gravity of the half headform were recorded by three uniaxial accelerometers (9264B, Piezoresistive Accelerometer, Endevco Meggitt, CA, USA). All instrument data channels were sampled at a rate of 20,000 Hz, before being zeroed and filtered based on ISO 6487 recommendations. Data capture was synchronised using a contact trigger.

2.13 Data Analysis

Results compared the safety performance of the helmeted headform against current legislative performance criteria and the selected published injury thresholds. Results presented for each test include the peak resultant linear accelerations of the helmeted headform.

3 Results

All helmet impact tests performed by this study were found to be compliant with current legislative performance criteria when impacted from the legislative drop height (1.5 m), regardless of the impact anvil shape. The remaining results are presented in two key sections; the effect of drop height and impact anvil shape on outcomes and the influence of compound impacts on outcomes.

When considering the effects of drop height on outcomes, it is clear that higher impact energies caused greater peak linear headform accelerations, independent of impact anvil shape (Figure 2). Impact anvil shape was, however, found to affect outcomes at higher impact energies, with kerbstone anvil impacts causing greater peak linear accelerations than flat anvil impacts at drop heights of 2.5 m or greater. Impact partner shape, to a lesser extent, also affected outcomes at lower impact energies, as impacts against the kerbstone anvil resulted in slightly lower peak accelerations at drop heights of 2.0 m or less. It can also be seen, from Figure 2, that there was a greater variance for drop tests performed at higher impact energies.

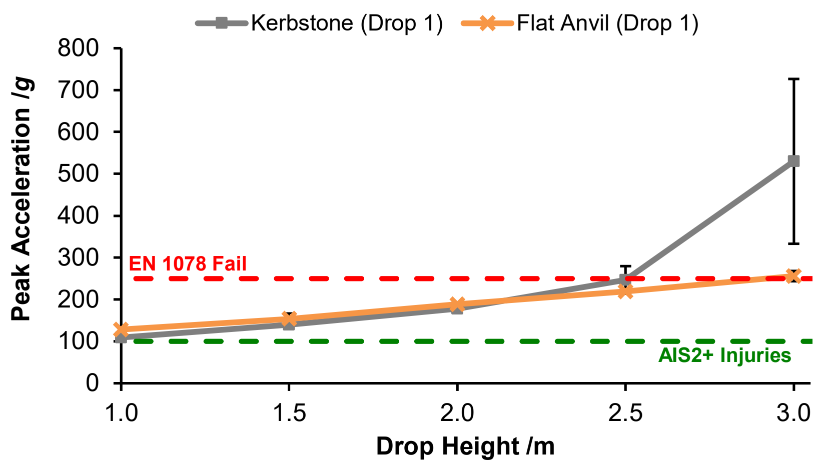

Figure 2: Mean peak linear headform accelerations compared to drop height for impacts against flat and kerbstone anvils during the first impact (Drop 1) only. The 250 *g* threshold line represents the pass/fail criterion specified by EN 1078, whilst the 100 *g* threshold line represents the AIS2+ injury criteria specified by Newman (1980) (BSI, 2012). Error bars represent the 95% confidence intervals of the mean.

The influence of compound impacts on helmet safety performance is illustrated in Figure 3. Whilst the majority of helmet impacts did not exceed current legislative performance criteria, two compound impacts from the kerbstone-kerbstone impact anvil combination exceeded the current EN 1078:2012+A1:2012 pass/fail criterion. Both helmets were, however, impacted at energies far exceeding that currently specified for kerbstone anvils by EN 1078:2012+A1:2012 (3 m vs. 1.06 m drop heights).

When the same impact anvils were used in the first and compound impacts (Figure 3), greater peak linear headform accelerations were measured during the compound impact when compared to the peak accelerations measured when different anvils were used. The impact energy of the first impact was also found to influence the accelerations experienced during the compound impact. For three impact anvil shape combinations (flat-flat, flat-kerbstone, kerbstone-kerbstone), the peak linear headform accelerations experienced during the compound impact increased when compared to the preceding impact from higher drop heights, with this increase accompanied by a greater variance. No such differences were found for the kerbstone-flat impact anvil combination.

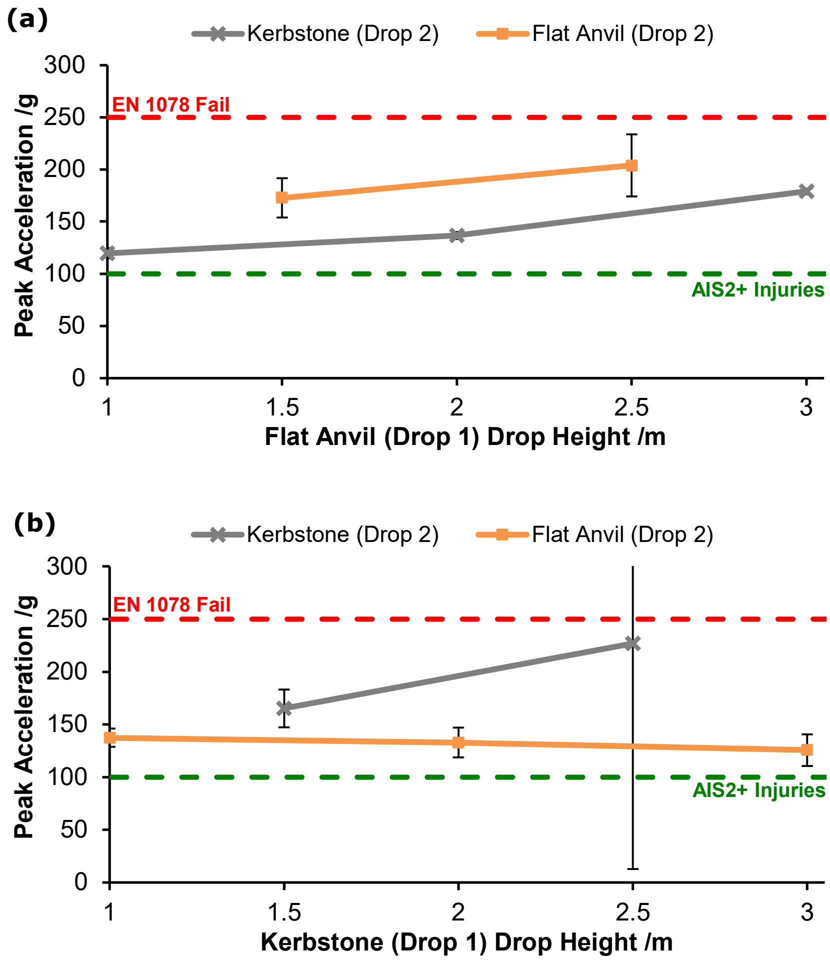

Figure 3: Mean peak linear headform accelerations for the compound impact (Drop 2) against the flat and kerbstone anvils compared to the drop height of the first impact (Drop 1) against the (a) flat and (b) kerbstone anvils. The 250 *g* threshold line represents the pass/fail criterion specified by EN 1078, whilst the 100 *g* threshold line represents the AIS2+ injury criteria specified by Newman (1980) (BSI, 2012). Error bars represent the 95% confidence intervals of the mean.

4 Discussion

4.1 Key Findings

4.1.1 Influence of Impact Energy and Impact Partner Shape

The results from this research illustrate that greater peak linear headform accelerations are caused by increased impact energies. Impact partner shape was also found to affect outcomes at greater impact energies. Anvil shapes with smaller contact areas (i.e. the kerbstone anvil) caused greater peak linear accelerations, and resulted in a greater variance, at drop heights of 2.5 m or greater. Impact partner shape, to a lesser extent, also affected outcomes at lower energy impacts, as shapes with smaller contact areas resulted in slightly lower head accelerations at drop heights of 2.0 m or less.

Although an increase in headform accelerations should clearly be expected at higher impact energies, it should be noted that the head acceleration injury threshold of 250 *g* (as adopted by EN 1078:2012+A1:2012) was only exceeded when helmets were tested at drop heights of 2.5 m or greater (when compared to drop heights of 1.5 m/1.06 m in current standards). Furthermore, it is also clear from the results that the kerbstone anvil began to cause the helmet structure to bottom out at drop heights of 2.5 m or greater. This resulted in the transfer of loads directly to the headform, causing a sharp increase in the instantaneous accelerations experienced by the headform, and a greater variance, due to the helmets bottoming out at different instants during the impact.

These differences in performance were primarily due to the increasing levels of damage caused to the helmet by the kerbstone anvil at higher impact energies. The kerbstone anvil, for the same impact energy, spread loads over a much smaller surface area than the flat anvil. This resulted in the greater penetration of the helmet by the anvil, causing damage to the expanded polystyrene (EPS) helmet structures at greater depths for a given impact energy. At drop heights of 2.5 m or greater, the extensive damage caused by the kerbstone anvil resulted in the transfer of loads directly to the headform during the impact. At drop heights of 2.0 m or less, however, the smaller surface area of the kerbstone anvil caused lower opposing forces from the helmet structure, which in turn slightly reduced the peak head accelerations when compared to the flat anvil.

4.1.2 Influence of Compound Impacts

When observing the effects of the damage caused by the first impact (drop 1) on the outcomes of a compound impact (drop 2) at the same location, two variables clearly influenced the safety performance of cycle helmets. Firstly, the greater the overlap in impact anvil shape, the greater the peak linear accelerations observed during the compound impact. Secondly, if impact anvil shapes extensively overlapped, the greater the energy of the initial impact the greater the peak linear accelerations observed during the compound impact.

When considering compound impacts, the extent that the impact partner shapes overlap was found to influence outcome (Figure 4). The use of the flat anvil for the initial impact resulted in large areas of damage to the EPS helmet structure. Thus, when impacting again with the flat anvil, the second impact almost entirely strikes the already damaged part of the helmet.

This results in the helmet bottoming out at an earlier point during the impact and the transfer of loads directly to the headform. When the kerbstone is used for the second impact, however, a proportion of the anvil engages with undamaged EPS material, resulting in a reduction in the accelerations experienced by the headform when compared to the flat anvil impact.

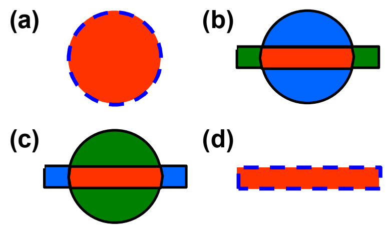

Figure 4: Schematic of impact partner shape overlap areas for the following impact combinations (a) flat-flat, (b) flat-kerbstone, (c) kerbstone-flat and (d) kerbstone-kerbstone. The first impacts are illustrated in blue, overlapping compound impact areas are red and non-overlapping compound impact areas are green.

When the kerbstone anvil was used for the first impact and flat anvil for the compound impact, a large area of the anvil struck non-damaged material, resulting in no change in peak linear headform acceleration. This was not the case, however, when the kerbstone anvil was used for the compound impact. This resulted in a focussed impact directly onto an area of already highly damaged material. This impact mechanism resulted in loads being transferred almost immediately to the headform and caused a large variation in the peak accelerations observed during the compound impact.

The impact energy of the first impact was also found to influence peak linear headform accelerations during the compound impact. For three impact anvil shape combinations (flat-flat, flat-kerbstone, kerbstone-kerbstone), the peak linear headform accelerations experienced during the compound impact increased following an impact from a greater drop height, with this increase also matched by greater intra-sample variation. This was due to the greater levels of damaged caused by the higher impact energies absorbed during the initial impact. No such differences were found for the kerbstone-flat impact anvil combination, however, due to the reasons explained in the previous paragraph.

It is important to note that, considering that the drop height of a compound impact was only 1 m, compound impacts were observed to considerably increase the risks of head injury when compared to the initial impact. The exploration of this trend across other compound impact energies and with offsets between the initial and compound impact locations would be of further value to the research community.

4.2 Comparison with Relevant Literature

Several key studies have evaluated the association between head injury risk and drop height during cycle helmet headform drop tests which may be compared to the results established by this study. DeMarco *et al.* (2016) measured the impact performance of 13 different cycle helmet models at impact speeds ranging from 1-10 $m \cdot s^{-1}$ onto a flat anvil for 127 different helmeted headform drop tests. The linear accelerations observed by DeMarco et al. (2016) in the anterior-temporal region were similar to those observed by this study for all impacts against a flat anvil. Both studies observed a linear relationship between the peak linear headform accelerations up to 2.5 m (~7 m·s^{-1}) drop heights, before headform accelerations rapidly increased at higher drop heights.

These results were further supported by Cripton *et al*. (2014), who found that, during drop tests against flat anvils from heights of 1-3 m, the frontal aspect of the helmeted headform experienced peak linear accelerations of 125-243 *g*. This closely compares with the range of peak linear headform accelerations (128-256 *g*) observed for the same drop height range in this study. Finally, Mills and Gichrist (2008)investigated the linear accelerations experienced during helmeted headform drop test impacts to the crown, frontal and lateral aspects of several cycle helmets. During 4.5 m·s^{-1} linear impacts to these impact locations, peak linear accelerations were found to be 148 *g*, 125-129 *g* and 135-138 *g*. When compared, this study found similar results, with 1 m (~4.42 m·s^{-1}) drop tests to the temporal aspects of the helmet resulting in peak linear accelerations of 109-128 *g*.

Whilst there are a number of studies that investigate the relationship between impact energy (i.e. drop test height) and outcomes, confirming this aspect of the study, neither the influence of impact energy on kerbstone anvil impacts nor the effect of compound impacts have ever been evaluated for helmeted headform impacts. The results from the cycle helmets tested by this research are therefore in general agreement with results from the cycle helmet drop tests performed across the literature when using comparable experimental procedures. This study does, however, extend previous research through evaluating the role of the impact partner shape across a range of drop heights and the influence of compound impacts on injury risks. This illustrates both the novelty of this research and the reproducible nature of the experimental procedures used throughout.

4.3 Implications for Advanced Cycle Helmet Testing Protocols

This research quantifies how helmet safety performance can vary with impact energy, impact partner shape and compound impacts (when a helmet is impacted multiple times at the same location). Although this research provides guidance on what effect these variables have on outcome, it may also be used to identify what tests may be unsuitable for future advanced cycle helmet testing protocols.

Poor repeatability was observed when the helmet was impacted against the kerbstone anvil from a drop height of 2.5 m or greater. This was also the case when the same impact anvils were used in both the first and compound impacts across the drop heights. As differences between outcomes were relatively small, such variance in outcomes can preclude the ability of a rating scheme to differentiate between the safety performances of different helmet models. As repeatable outcomes are critical to a well-designed test and assessment protocol, these large variations in measured helmet performance may prohibit the inclusion of these tests in advanced protocols.

By impacting helmeted headforms from a height of 3.0 m against a flat anvil, this study evaluates the safety performance of cycle helmets during high energy linear impacts. The helmet model used in this study only exceeded the current EN 1078:2012+A1:2012 pass/fail criterion when tested against kerbstone anvils at this particular impact energy. Impact tests that are performed from these drop heights onto flat anvils could therefore be a key addition to the array of tests used to differentiate between safety performances of different cycle helmet models.

It is also clear that, should cycle helmets provide additional safety performance qualities that better protect the head during multiple impacts (e.g. expanded polypropylene (EPP) material), the compound impact tests described in this research could be a key addition to the array of tests to be used for differentiating between the protective qualities of helmet models.

Further comparisons against cyclist collision data are required, however, to evaluate the relative importance of each test and assessment protocol. Weightings should be developed to ensure that the outcomes of each test are given a proportional weighting that is based on the relative real-world importance of each injury mechanism.

4.4 Limitations

The research methods adopted by this research are limited by a number of necessary assumptions and simplifications. The biomechanical response of the headform that was used throughout this research may not accurately represent the response of the head during impact, whilst the lack of a flexible neck anchorage may also result in a less biofidelic response (Ghajari *et al.*, 2013). Despite these issues, the key objective for this research was to compare the differences between the responses of the headform during different impact configurations. It would therefore be expected that, as all experiments used the same headform, any differences in response would be highlighted, regardless of headform or neck biofidelity.

Although the injury thresholds used to analyse these results are founded upon the best available evidence base, the individual methodological limitations of these studies must also be acknowledged. There has been international debate for many years over the use of appropriate predictors of traumatic brain injury, with the kinematic injury criteria and finite element analysis (FEA) approaches seen as the most fundamental to the field (Yoganandan *et al.*, 2014). As there has been no definitive international acceptance of a single approach, this study adopted the use of the kinematic head injury criteria defined by Newman (1980).

Finally, the helmet impact configurations evaluated by this study may not fully represent those actually experienced during cyclist collisions. This particular cycle helmet model, which was specifically designed to pass EN 1078:2012+A1:2012, may therefore perform worse if impacted at non-test locations, with greater impact energies or on surfaces inclined at different angles then those investigated during this study, thus potentially increasing the injury risks. Different helmet models may also perform differently under the same impact conditions. Further research is therefore required to investigate the potential effects of other impact configurations.

5 Conclusions

Impact energies, impact partner shapes and compound impacts have all been shown to affect the safety performance of cycle helmets. Higher impact energies were observed to result in greater peak linear headform accelerations. Although a considerable increase in headform accelerations was caused by the kerbstone anvil for drop heights of 2.5 m or greater, high energy impacts onto the flat anvil only exceeded current legislative safety performance criteria when impacted from a drop height of 3.0 m. Compound impacts were principally affected by the proportion of the undamaged EPS material engaged by the compound impact. Advanced testing protocols should recognise and assess the relative safety performance of cycle helmets against these variables.

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Appendix A

Table 1: Test matrix

Test #	Helmet #	Impact Location	Drop Height /m		Anvil Type	
			Drop 1	Drop 2	Drop 1	Drop 2
1	1	Left Temporal	1	1	Flat	Kerb
2	1	Right Temporal	1	1	Flat	Kerb
3	2	Left Temporal	1	1	Flat	Kerb
4	2	Right Temporal	1.5	1	Flat	Flat
5	3	Left Temporal	1.5	1	Flat	Flat
6	3	Right Temporal	1.5	1	Flat	Flat
7	4	Left Temporal	2	1	Flat	Kerb
8	4	Right Temporal	2	1	Flat	Kerb
9	5	Left Temporal	2	1	Flat	Kerb
10	5	Right Temporal	2.5	1	Flat	Flat
11	6	Left Temporal	2.5	1	Flat	Flat
12	6	Right Temporal	2.5	1	Flat	Flat
13	7	Left Temporal	3	1	Flat	Kerb
14	7	Right Temporal	3	1	Flat	Kerb
15	8	Left Temporal	3	1	Flat	Kerb
16	8	Right Temporal	1	1	Kerb	Flat
17	9	Left Temporal	1	1	Kerb	Flat
18	9	Right Temporal	1	1	Kerb	Flat
19	10	Left Temporal	1.5	1	Kerb	Kerb
20	10	Right Temporal	1.5	1	Kerb	Kerb
21	11	Left Temporal	1.5	1	Kerb	Kerb
22	11	Right Temporal	2	1	Kerb	Flat
23	12	Left Temporal	2	1	Kerb	Flat
24	12	Right Temporal	2	1	Kerb	Flat
25	13	Left Temporal	2.5	1	Kerb	Kerb
26	13	Right Temporal	2.5	1	Kerb	Kerb
27	14	Left Temporal	2.5	1	Kerb	Kerb
28	14	Right Temporal	3	1	Kerb	Flat
29	15	Left Temporal	3	1	Kerb	Flat
30	15	Right Temporal	3	1	Kerb	Flat

Advanced Cycle Helmet Testing Protocols: Effects of Linear Impact Energy and Compound Impacts on Cycle Helmet Safety

Background: The effects of impact energy, impact partner shape and compound impacts (where a single location is impacted multiple times) on cycle helmet safety performance during linear impacts are not well characterised by the literature.

Objective: Establish the influence of impact energy and compound impacts on injury risk during flat and kerbstone anvil impacts.

Methods: Linear wire-guided drop tests were implemented by mounting helmets to a hemispherical headform, before impacting the left/right temporal regions of the helmet against flat and kerbstone anvils. Two consecutive drops of each helmet were performed against each location. The first drop was performed from heights ranging between 1-3 m (in 0.5 m increments), whilst the second drop was performed from a 1 m drop height. Peak linear headform accelerations were recorded.

Results: For the first impact, higher impact energies resulted in greater peak headform accelerations, regardless of anvil shape. Anvil shape affected outcomes at higher impact energies, as the kerbstone anvil resulted in greater peak accelerations at drop heights of >2.0 m. When observing the effects of the initial impact on the second impact, two variables affected safety performance. Firstly, the greater the energy of the first impact, the greater the peak accelerations during the lower energy compound impact. Secondly, the greater the overlap in impact partner shape, the greater the accelerations during the compound impact.

Conclusions: Impact energies, impact partner shapes and compound impacts all affect helmet safety performance during linear impacts. Advanced testing protocols should consider assessing helmet safety performance against these variables.

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