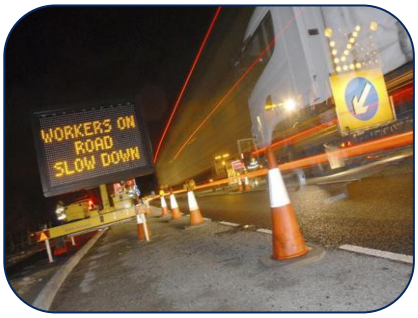
Transport Research Laboratory

Creating the future of transport



PUBLISHED PROJECT REPORT PPR759

Safety Testing of Helmet-Mounted Cameras

P Martin, V StClair and C Willis

Prepared for: BBC

Project Ref: PPR759

Quality approved:

Lisa Collins
(Project Manager)

David Hynd
(Technical Referee)

Disclaimer

This report has been produced by the Transport Research Laboratory under a contract with the BBC. Any views expressed in this report are not necessarily those of the BBC.

The information contained herein is the property of TRL Limited and does not necessarily reflect the views or policies of the customer for whom this report was prepared. Whilst every effort has been made to ensure that the matter presented in this report is relevant, accurate and up-to-date, TRL Limited cannot accept any liability for any error or omission, or reliance on part or all of the content in another context.

When purchased in hard copy, this publication is printed on paper that is FSC (Forest Stewardship Council) and TCF (Totally Chlorine Free) registered.

Contents amendment record

This report has been amended and issued as follows:

Version	Date	Description	Editor	Technical Referee
1.0	08/06/2015	Draft report - Version 1	PM	DH
2.0	10/08/2015	Draft report - Version 2	PM	DH
3.0	09/09/2015	Final report	PM	DH

Executive Summary

Helmets are a vital item of personal protective equipment that aim to reduce the severity of head injuries through the provision of adequate head protection. The attachment of non-approved rigid components, such as helmet-mounted cameras, to a climbing helmet may, however, alter the helmet's carefully designed and certified protective properties. No scientific evidence currently exists, however, that quantifies the risks associated with helmet-mounted cameras, whilst helmet and camera manufacturers advise that cameras should only be attached to helmets at the wearer's own risk. With the increasing use of helmet-mounted cameras to record footage for British Broadcasting Corporation (BBC) productions, the BBC wished to investigate the potential safety implications associated with climbing helmet-mounted cameras.

The primary objectives of this project were to establish the potential effects of helmet-mounted cameras on the injury risks of falling object strikes to the helmet and falls from height onto flat and angled surfaces. These objectives were achieved with the completion of four experimental studies that established the safety performance of helmet-mounted cameras, as follows (and summarised by the schematic in Figure 1 overleaf):

- **Study 1** performed *falling striker tests* with hemispherical and flat strikers (i.e. simulating objects falling onto the helmet) to assess the effects of helmet-mounted cameras during falling object strikes that can result in potentially injurious forces.
- **Study 2** performed *linear falling headform drop tests* (i.e. simulating head-first falls onto a flat surface) onto a flat anvil, to investigate the effects of helmet-mounted cameras during falls onto flat surfaces that can induce potentially injurious accelerations of the head.
- **Study 3** performed *oblique falling headform drop tests* (i.e. simulating head-first falls onto an angled surface) onto a steel bar anvil, angled at 15° to the vertical, to evaluate the effects of helmet-mounted cameras during falls onto angled surfaces that can induce potentially injurious rotations of the head.
- **Study 4** performed three further "*out-of-position*" *tests* to assess the performance of hardshell climbing helmets when loaded in non-standard impact configurations.

All experimental procedures were developed through the adaptation of current European testing standards and regulations. To represent the breadth of currently available helmet designs, three helmet categories (hardshell, foam and hybrid) were evaluated for each experimental study. These helmets were impacted at three test locations (vertex, front and side), using five different camera mounting combinations and three control tests. Impacts to the vertex of the helmet were performed from drop heights of 2 m, whilst impacts to the front and sides of the helmet were performed from drop heights of 0.5 m. Both strikers weighed 5 kg, whilst the instrumented headforms weighed 4.8 kg. The BBC provided all climbing helmets, cameras and mounts, whilst specifying all helmet camera mounting combinations based on commonly observed mounting practice.

Data was collected for the forces, linear accelerations, rotational velocities and rotational accelerations experienced by the headform during each study. Results compared the safety performances of the camera mounted helmets both against the control helmets and against legislative performance criteria (i.e. minimum levels of protection specified by European standards and regulations) and selected published injury thresholds (i.e. additional criteria that relate to a 50% risk of either a simple linear fracture of the skull or a loss of consciousness for <1 hour). Finally, the proportion of cameras observed to detach from the helmet, and the detachment mechanism, were also documented.

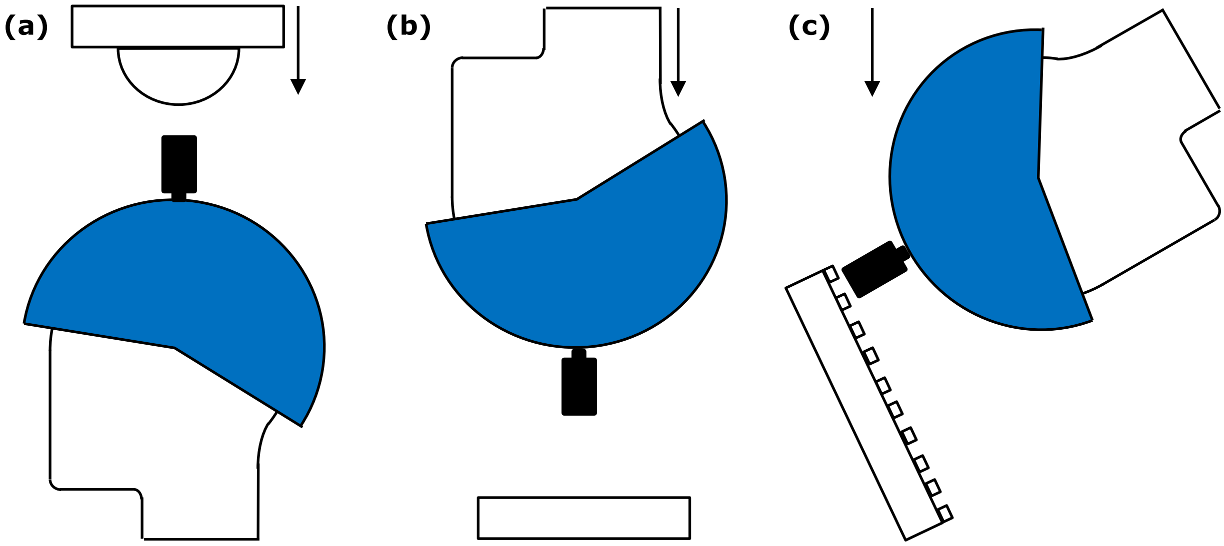


Figure 1: Schematics for the (a) falling striker tests, (b) linear falling headform drop tests and (c) oblique falling headform drop tests performed for the camera mounted at the vertex of the climbing helmet configuration

All climbing helmet and camera combinations investigated by this project were compliant with current legislative performance criteria, whilst no combination was found to exceed the selected published injury thresholds. When compared to the control helmets, no increase in head injury risk was found with the forces transferred to the headform during the falling object strikes to the helmet-mounted cameras (Study 1). Falls onto flat surfaces that impacted the helmet-mounted camera were, in general, found to reduce the head injury risks associated with linear and rotational accelerations, whilst increasing the risks related to rotational velocities (Study 2). Finally, falls onto angled surfaces that impacted the helmet-mounted camera were, in general, observed to reduce the head injury risks associated with linear accelerations, whilst increasing the risks related to the longitudinal forces, rotational velocities and rotational accelerations (Study 3). Across all experimental studies, cameras detached from the helmet in 40% of tests; with the majority of detachments (66%) occurring during the higher energy vertex impacts. These results therefore indicate that, although the mounting of helmet cameras resulted in a potential increase in head injury risk during falls, this increased risk did not result in any helmet and camera combination investigated by this project exceeding any legislative performance criteria or selected published injury threshold.

The three "out-of-position" tests performed by this project were, however, associated with the greatest risks of head injury, with off-centre falling striker tests to the vertex of the helmet, higher energy linear falling headform drop tests to the side impact location and front-mounted, rear-facing, helmet-mounted cameras, all associated with outcomes that exceeded at least one legislative performance criterion or published injury threshold (Study 4). In particular, the front-mounted, rear-facing, helmet-mounted camera tested by this Study broke away and impacted the headform face, even during a low energy impact, which may have serious consequences for wearers. These results emphasise that the effectiveness of climbing helmet protection may be significantly compromised when either inappropriately used (i.e. poorly mounted helmet cameras) or involved in "out-of-position" impacts where the helmet is loaded in a non-standard impact configuration.

Recommendations:

The results of this project indicate all climbing helmet-mounted camera configurations investigated by this project may be mounted to all three helmet models, and at all three impact locations, without increasing the risks of head injury beyond current legislative performance requirements or published injury thresholds. During the project, the front-mounted, rear-facing, helmet-mounted camera configuration was further identified to be susceptible to breaking away from the helmet and impacting the face of the wearer even during low energy impacts.

It must be noted that these recommendations and results are valid only for the impact configurations investigated by this project and that there are other conceivable scenarios where the mounting of a camera may compromise the safety of a helmet (as evidenced by Study 4). It is important to note that these recommendations and results must also be taken in the context of the limitations of the approach adopted by this project. TRL therefore takes no responsibility for the actions of individuals, whilst wearing either a helmet or helmet-mounted camera, and advise that activity-specific risk assessments are always performed. Further testing should also be performed to establish the effects of any additional helmet and camera mounting configurations that do not correspond to those already evaluated by this project.

Table of Contents

1 Introduction

Outdoor adventure activities, such as mountaineering, climbing and abseiling, are closely associated with an increased risk of head injuries resulting from falls and falling object strikes (Nelson & McKenzie, 2009). The use of helmets during such activities is a risk management practice that intends to protect the wearer in the event of a fall or if struck by a falling object. Although accidents resulting in head injuries remain rare (4.5-17.4%) (Nelson & McKenzie, 2009; Lack, et al., 2012; Locker, et al., 2004), such head injuries tend to be severe and can often result in hospitalisation (Bowie, et al., 1988).

Advances in digital camera technology have, in recent years, transformed the helmet-mounted camera market, with both lens units and high-definition video recording devices becoming smaller and cheaper. Consequently the popularity of helmet-mounted cameras has exploded, with a reported 5.5 million units shipped globally in 2014 (Statista, 2015). Helmet-mounted cameras have since become a valuable device for recording point-of-view video footage for production companies, particularly in situations where traditional hand-held cameras may prove difficult to operate.

Helmets are a vital item of personal protective equipment that aim to reduce the severity of head injuries through the provision of adequate head protection. The attachment of non-approved rigid components, such as helmet-mounted cameras, to a climbing helmet may, however, alter the helmet’s carefully designed and certified protective properties. If impacted, helmet-mounted cameras may therefore have the potential to influence the biomechanics of accidents and affect the risks or severities of head injuries. Prior to this project, however, no previous research has been found to establish the consequences of helmet-mounted cameras on head injury biomechanics during impact, whilst helmet and camera manufacturers both advise that cameras are only mounted to the helmet at the wearer’s own risk.

2 Aims & Objectives

With the increasing use of helmet-mounted cameras to record video footage for British Broadcasting Corporation (BBC) productions, the BBC wished to investigate the potential safety implications associated with climbing helmet-mounted cameras. The primary aim of this project was to establish the potential effects of helmet-mounted cameras on the injury risks of falls from height onto flat and angled surfaces and falling object strikes to the helmet. To achieve this aim, the following objectives were identified:

1. Evaluate the effects of helmet-mounted cameras on the shock absorbing performance of climbing helmets (i.e. when struck by a falling object)
2. Determine the effects of helmet-mounted cameras on the linear impact absorbing performance of climbing helmets (i.e. from falls onto flat surfaces)
3. Analyse the effects of helmet-mounted cameras on the oblique impact absorbing performance of climbing helmets (i.e. from falls onto angled surfaces)
4. Assess the performance of climbing helmets during “out-of-position” impacts (i.e. during non-standard impact configurations)

These objectives were achieved through the completion of four Work Packages focussed on investigating each individual objective through the use of falling striker and headform tests. A “Letter of Advice”, supported by this report and advising the BBC on current best practices for attaching helmet-mounted cameras to a climbing helmet, is the expected output from this project.

3 Methods

3.1 Climbing Helmets

The majority of modern climbing helmets fit into one of three categories (hardshell, foam or hybrid), which can be separated by their unique mechanical properties. Further details on the specific helmet designs selected for assessment in this project (Petzl VERTEX® VENT (hardshell), Petzl METEOR (foam) and Petzl ELIOS (hybrid)) and their mechanical properties are provided in Appendix A.3.

3.2 Helmet Testing Standards

The experimental procedures and legislative performance criteria adopted by this project were based on the helmet testing standards outlined below, with further details provided in Appendix A.1:

- EN 12492:2012. Mountaineering equipment - Helmets for mountaineers - Safety requirements and test methods.
- EN 1078:2012+A1:2012. Helmets for pedal cyclists and for users of skateboards and roller skates.
- UN ECE Regulation 22.05 (Supplement 2, Revision 4, Amendment 1). Uniform provisions concerning the approval of protective helmets and their visors for drivers and passengers of motor cycles and mopeds.

3.3 Published Injury Thresholds

Published injury thresholds were further selected to provide criteria to relate outcomes to a 50% risk of AIS2 head injuries (i.e. either a simple linear fracture of the skull or loss of consciousness for <1 hour) (AAAM, 2008). Further details on these selected published injury thresholds are provided in Appendix A.2.

3.4 Impact Locations

Three impact locations, based on EN 12492:2012 requirements and current BBC helmet camera mounting practice, were evaluated by this project. These locations included the vertex of the helmet and frontal and lateral locations angled at 30° from the transverse plane and toward the front and side of the helmet (impact points V, F and L in Figure 10, Appendix A.4).

3.5 Helmet Camera Mounting

The helmet-mounted camera used in this project was a GoPro Hero4 camera housed in a Skeleton HD impact protection case. The shock and impact absorption performance of all three climbing helmet categories were assessed for each Work Package across all three impact locations using a total of five camera mounting options and three control tests (Table 1 & Table 2, Appendix B). No cameras were required for the control test helmets.

3.6 Headform

All tests used an instrumented EN 960:2006 compliant 575 mm circumference headform (4.7 kg mass).

3.7 Helmet Adjustment

All climbing helmets were adjusted to the headform size and positioned according to the manufacturer's instructions. A load of 50 N was applied to the vertex of the helmet to adjust the helmet such that there was contact between the inner surface of the helmet and the headform vertex. The retention system was then adjusted under the chin of the headform and, as defined in the standards, any strapping tightened as much as possible.

3.8 Test Headform Positioning

For the control test helmets, the helmeted headform was positioned such that the test helmet was impacted at the desired impact location with the normal reaction force acting through the headform centre of gravity. For the camera mounted helmets, the camera was positioned on the helmeted headform such that a "worst case scenario" impact on the camera (as judged by the investigator) was performed.

3.9 Testing Procedures

3.9.1 Work Package 1: Falling Striker Tests

Work Package 1 adapted EN 12492:2012 to direct both the experimental procedures and legislative performance criteria. The test helmet was fitted and adjusted to the headform before mounting on a customised solid steel base to allow the helmeted headform to be positioned for testing at all three impact locations. Hemispherical steel strikers (5 kg mass) were dropped in a guided free-fall from heights of 2 m onto the vertex of the helmet, whilst flat steel strikers (also 5 kg mass) were dropped from 0.5 m heights onto the frontal and lateral helmet impact test locations. The axial forces transmitted to the headform during impact were recorded via a triaxial force transducer, whilst the velocity of the striker was continuously recorded by a uniaxial accelerometer mounted on the striker carriage. Further details on the methods used by Work Package 1 are described in Appendix A.8 and summarised by the schematic in Figure 2 overleaf.

3.9.2 Work Package 2: Linear Headform Drop Tests

Work Package 2 adapted EN 1078:2012+A1:2012 and EN 12492:2012 to direct both the experimental procedures and legislative performance criteria. The test helmet was fitted and adjusted to the headform before mounting in the drop carriage to position the helmeted headform for testing at all three impact locations. The helmeted headforms (circa 5 kg mass) were dropped onto a flat steel anvil in a guided free-fall from drop heights of 2 m for the vertex of the helmet and 0.5 m for the frontal and lateral impact test locations. The linear accelerations and rotational velocities experienced at the centre of gravity of the headform were recorded by three uniaxial accelerometers and three uniaxial angular rate sensors during impact. Further details on the methods employed in Work Package 2 are described in Appendix A.9 and summarised by the schematic in Figure 2 overleaf.

3.9.3 Work Package 3: Oblique Headform Drop Tests

Work Package 3 adapted UN ECE Regulation 22.05 (method A) and EN 12492:2012 to direct both the experimental procedures and legislative performance criteria. The test helmet was fitted and adjusted to the headform before mounting on the drop carriage to allow the helmeted headform to be positioned for testing at all three impact locations. The helmeted headforms (circa 5 kg mass) were dropped onto a steel bar anvil angled 15° to the vertical in a guided free-fall from drop heights of 2 m for the vertex of the helmet and 0.5 m for the frontal and lateral impact locations. The linear accelerations and rotational velocities experienced at the centre of gravity of the headform were recorded by three uniaxial accelerometers and three uniaxial angular rate sensors during impact. Further details on the methods employed in Work Package 3 are described in Appendix A.10 and summarised by the schematic in Figure 2 below.

3.9.4 Out-of-Position Tests

Three "out-of-position" impact tests were also performed to investigate the effects of non-standardised impacts to the helmet (i.e. test configurations not compliant with the helmet testing standards). For consistency, all tests were performed on the hardshell helmet, including an off-centre falling striker impact to the top of the helmet (replicating the procedures in Section 3.9.1), a lateral linear headform drop test with the helmeted headform dropped from a height of 2 m (replicating the procedures in Section 3.9.2) and a frontal linear headform drop test performed with a front-mounted, rear-facing, helmet-mounted camera (also replicating the procedures in Section 3.9.2).

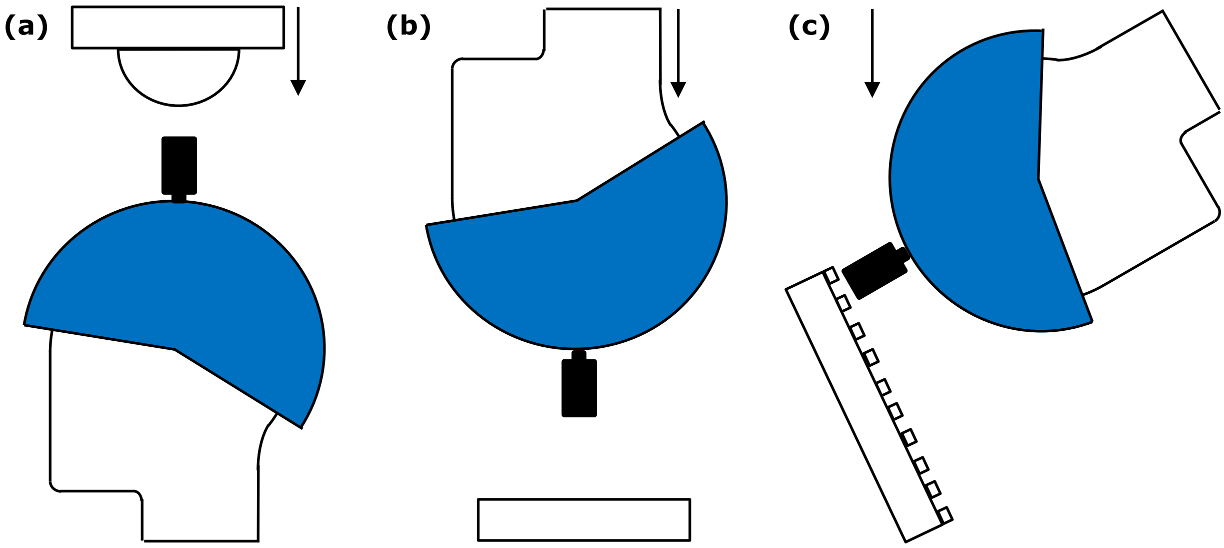


Figure 2: Schematics for the (a) falling striker tests, (b) linear falling headform drop tests and (c) oblique falling headform drop tests performed for the camera mounted at the vertex of the climbing helmet configuration

3.10 Data Processing

High speed video was captured for all tests at a frame rate of 1,000 frames per second. 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. Further details on the channel handling and data processing performed during this project are summarised in Appendix A.12.

3.11 Data Analysis

Results compared the safety performances of the camera mounted helmets both against the control helmets and against legislative performance criteria (i.e. minimum levels of protection specified by European standards and regulations) and selected published injury thresholds (i.e. additional criteria that relate to a 50% risk of either a simple linear fracture of the skull or a loss of consciousness for <1 hour).

3.11.1 Work Package 1: Falling Striker Tests

Results for each test include the initial impact kinetic energy, the peak impact force, the peak impact impulse, the proportion of cameras observed to detach from the helmet and the camera detachment mechanism.

3.11.2 Work Package 2: Linear Headform Drop Tests

Results for each test include the initial impact kinetic energy, the peak resultant linear acceleration, the head injury criterion (HIC_{15}), the peak resultant angular velocity, the peak resultant angular acceleration, the proportion of cameras observed to detach from the helmet and the camera detachment mechanism.

3.11.3 Work Package 3: Oblique Headform Drop Tests

Results for each test include the initial impact kinetic energy, the peak resultant linear acceleration, the head injury criterion (HIC_{15}), the peak resultant angular velocity, the peak resultant angular acceleration, the peak longitudinal force, the peak longitudinal impulse, the proportion of cameras observed to detach from the helmet and the camera detachment mechanism.

3.11.4 Out-of-Position Tests

Results for the off-centre falling striker test replicated those reported above in Section 3.11.1. Results for the linear headform drop tests performed using a 2 m drop test height on to the lateral impact test location and using a front-mounted, rear-facing, helmet camera replicated those reported above in Section 3.11.2.

4 Key Findings

The below findings are valid only for the specific climbing helmet models, helmet camera mounting options, impact locations, initial impact kinetic energies, loading mechanisms and impact surfaces investigated by this project. Tables providing full details for all the following key findings may be found in Appendix C.

Key Finding 1: No legislative performance criteria or injury thresholds were exceeded by any helmet and camera combination

All climbing helmet and camera combinations investigated by this project were compliant with current legislative performance criteria, whilst no combination was found to exceed the selected published injury thresholds.

The hybrid and hardshell control helmets resulted in the greatest peak impact force (7.8-7.9 kN) during the falling striker tests onto the vertex (Table 3), with no combination found to exceed the 10 kN performance criteria specified by EN 12492:2012.

The greatest linear head accelerations were experienced during impacts onto the vertex and frontal impact locations of the hardshell and hybrid control helmets. These values were greatest for the linear headform drop tests (198-189 *g*, Table 4 and Table 5), with no combination found to exceed the 250 *g* legislative performance criteria specified by EN 1078:2012+A1:2012 and no helmet-mounted camera combination exceeding the 100 *g* AIS2+ head injury threshold specified by Newman (1980). This was supported by HIC_{15} values, where the greatest HIC_{15} values occurred during the linear headform drop tests onto the vertex of the hardshell and hybrid control helmets (HIC_{15}: 906-817), with no combination observed to exceed the HIC_{15} injury threshold of 1000 for AIS2+ head injuries (Chinn, et al., 2001).

The greatest angular headform velocities and accelerations were, in general, experienced during the linear headform drop tests (Table 4 and Table 5). These values were greatest during impacts of the hardshell and hybrid control helmets at the lateral impact location (ω: 35-43 rads^{-1} and α: 5,994-5,859 rads^{-2}), with no combination found to exceed any specified 50% probability of AIS2+ concussion injury thresholds (Zhang, et al., 2004; Rowson, et al., 2012). Finally, during the oblique headform drop tests, no combination was observed to achieve >62% of the longitudinal force (2.5 kN) and impulse (12.5 Ns) legislative performance criteria specified by UN ECE Regulation 22.05 (Method A) for motorcycle helmets (Table 4 and Table 5).

Key Finding 2: Climbing helmet-mounted cameras do not increase the risks of injury associated with the forces transferred to the head during falling object strikes

When compared to the control helmets, the forces transferred to the helmeted headform during the falling object strike tests were not increased with the addition of a helmet-mounted camera (Figure 3). This suggests that, for the specific parameters investigated by this project, helmet-mounted cameras do not increase the injury risks associated with forces transferred to the head during falling object strikes to the climbing helmets. All investigated helmet-mounted camera combinations may therefore be worn without increasing the injury risks associated with the forces transferred to the head when struck on the helmet by falling objects (i.e. rock or ice falls) for the specific impact mechanisms investigated by this project.

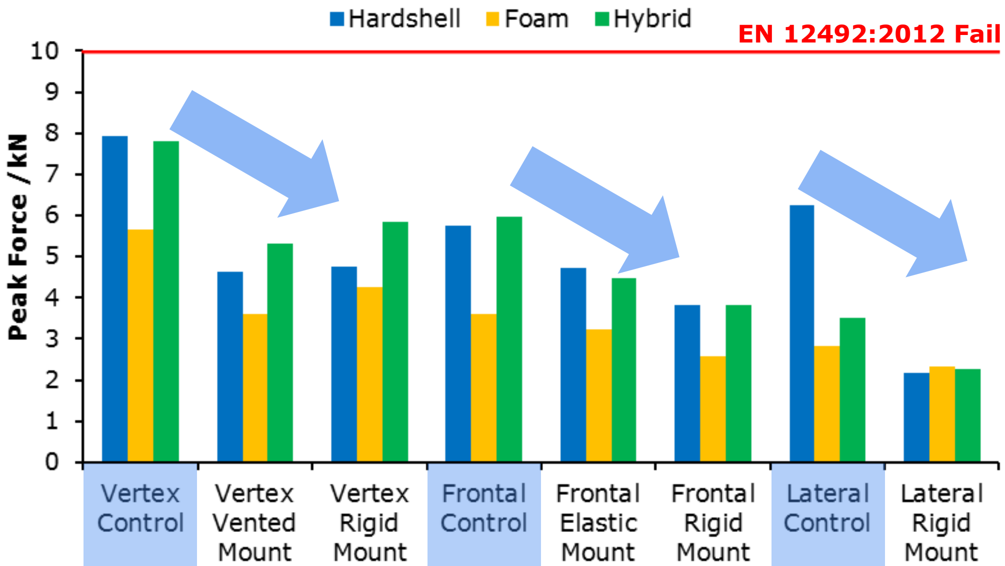


Figure 3: Comparison of the peak forces experienced by all climbing helmet and camera combinations during falling striker test impacts against the 10 kN criteria specified by EN 12492:2012

Key Finding 3: Climbing helmet-mounted cameras do not increase the risks of injury associated with linear accelerations during linear impacts

When compared to the control test helmets, the linear accelerations experienced by the helmeted headform during the linear drop tests were not increased with the addition of the climbing helmet-mounted camera (Figure 4). This was further supported by a similar relationship for HIC_{15} values calculated from the linear drop tests. This suggests that, for the specific parameters evaluated by this project, the helmet-mounted cameras tested by this project do not increase the injury risks associated with linear accelerations during linear impacts to the helmet. All investigated helmet-mounted camera combinations may therefore be worn without increasing the risks of injury associated with the linear head accelerations experienced during helmeted falls onto horizontal surfaces (i.e. falls onto flat floors/ground) for the specific impact mechanisms investigated by this project.

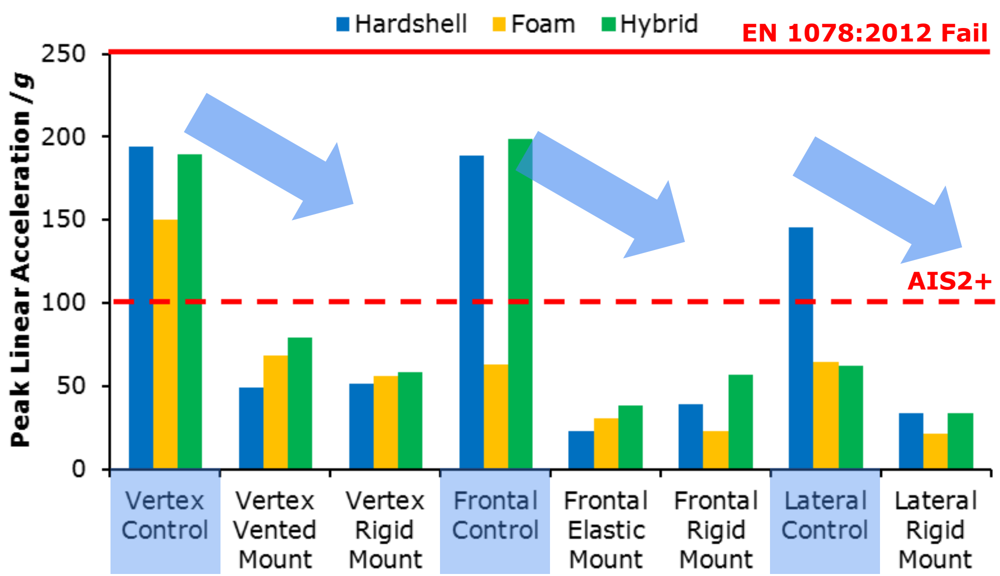


Figure 4: Comparison of peak linear accelerations experienced by all climbing helmet and camera combinations during linear headform drop test impacts against the 250 *g* AIS5+ (solid line) criteria and 100 *g* AIS2+ injury thresholds (dashed line) specified by EN 1078:2012+A1:2012 and Newman (1980)

Key Finding 4: Climbing helmet-mounted cameras have a mixed effect on the risks of injury associated with angular velocities and accelerations during linear impacts

When compared to control helmets, the addition of the helmet-mounted camera tested by this project was observed to have a mixed effect on the risks of injury associated with the angular velocities and accelerations experienced during linear impacts to the helmet (Figure 5, overleaf). It should be noted, however, that the two test combinations that verged on the lowest 50% probability of concussion threshold were impacts to the hardshell and hybrid control helmets at the lateral impact test location. All investigated helmet-mounted camera combinations may therefore be worn without exceeding injury thresholds associated with the rotational head accelerations and velocities experienced during helmeted falls onto horizontal surfaces (i.e. falls onto flat floors/ground) for the specific impact mechanisms investigated by this project.

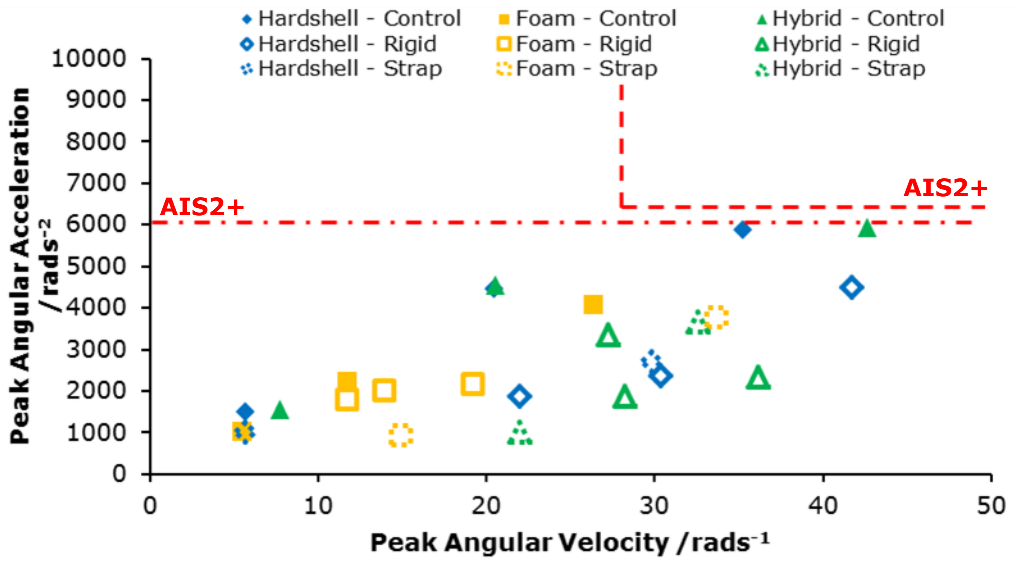


Figure 5: Comparison of the angular velocities and accelerations experienced by all climbing helmet and camera combinations during linear drop test impacts against 50% probability of AIS2+ concussion thresholds (dashed-line adapted from Rowson et al. (2012), dot-dashed line adapted from Zhang et al. (2004))

Key Finding 5: Climbing helmet-mounted cameras increase the risks of injury associated with both the longitudinal forces and impulses transferred to the head during oblique impacts

When compared to the control test helmets, the longitudinal forces experienced by the helmeted headform during the oblique drop tests were, in general, increased with the addition of a helmet-mounted camera (Figure 6). This was further supported by a similar relationship for peak longitudinal impulses (Figure 7, overleaf).

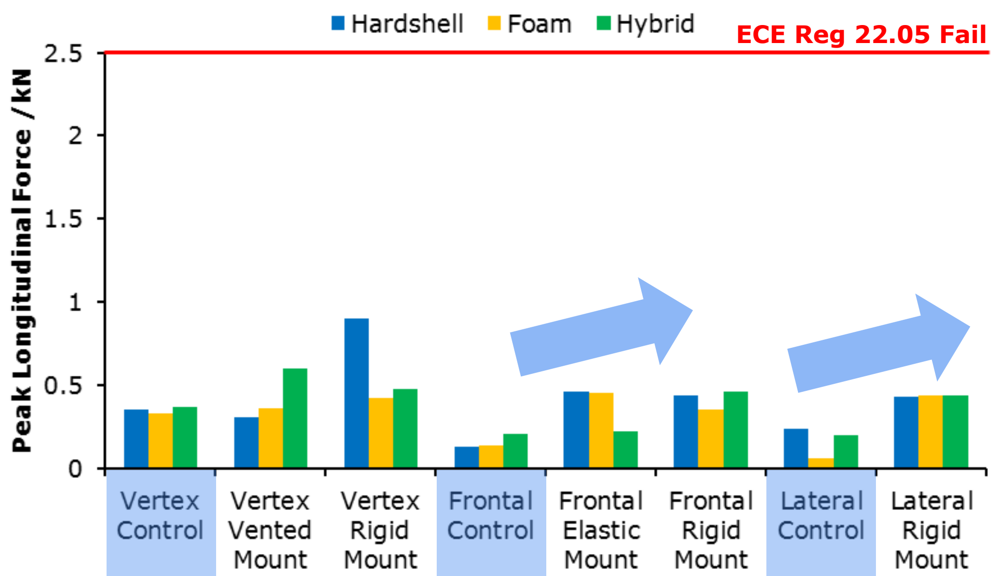


Figure 6: Comparison of the peak longitudinal forces experienced by all climbing helmet and camera combinations during oblique headform drop test impacts against the 2.5 kN criteria specified by UN ECE Reg 22.05

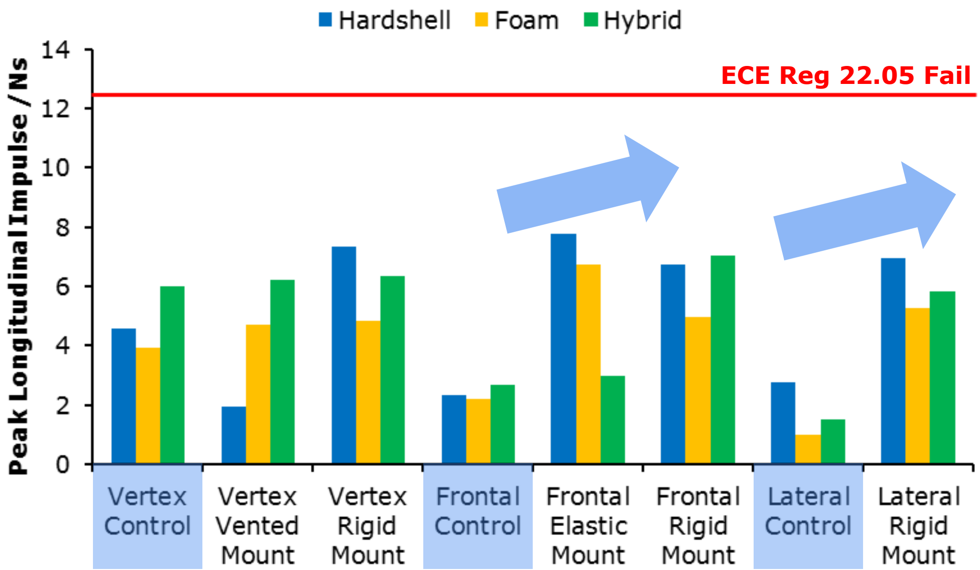


Figure 7: Comparison of the peak longitudinal impulses experienced by all climbing helmet and camera combinations during oblique headform drop test impacts against the 12.5 Ns criteria specified by UN ECE Reg 22.05

With the longitudinal forces experienced during oblique impacts failing to surpass 0.9 kN (2.5 kN legislative performance criteria) and longitudinal impulses failing to exceed 7.75 Ns (12.5 Ns legislative performance criteria), however, this increase is likely to have little effect on outcome. This suggests that, for the specific parameters evaluated by this project, the helmet-mounted camera configurations tested by this project, in general, only marginally increase the injury risks associated with longitudinal forces and impulses during oblique impacts to the climbing helmets. All investigated helmet-mounted camera combinations may therefore be worn without exceeding legislative performance criteria regulating the maximum longitudinal forces and impulses allowed during helmeted falls onto angled surfaces (i.e. falls onto angled floors or pendulum-like impacts with walls) for the specific impact mechanisms investigated by this project.

Key Finding 6: Climbing helmet-mounted cameras do not increase the risks of injury associated with linear accelerations during oblique impacts

When compared to the control climbing helmets, the linear accelerations experienced by the helmeted headform during the oblique drop tests remained, in general, unchanged with the addition of the helmet-mounted camera (Figure 8, overleaf). This was further supported by a similar relationship for the HIC_{15} values. With linear accelerations failing to surpass 36 *g* and no HIC_{15} value exceeding 19, however, any differences are likely to have negligible effect on the outcomes of oblique impacts. This suggests that, for the specific parameters assessed by this project, the helmet-mounted cameras tested by this project do not affect the injury risks associated with linear accelerations during oblique impacts. All investigated helmet-mounted camera combinations may therefore be worn without exceeding either the legislative performance criteria or the published head injury thresholds during helmeted falls onto angled surfaces (i.e. falls onto angled floors or pendulum-like impacts with walls) for the specific impact mechanisms investigated by this project.

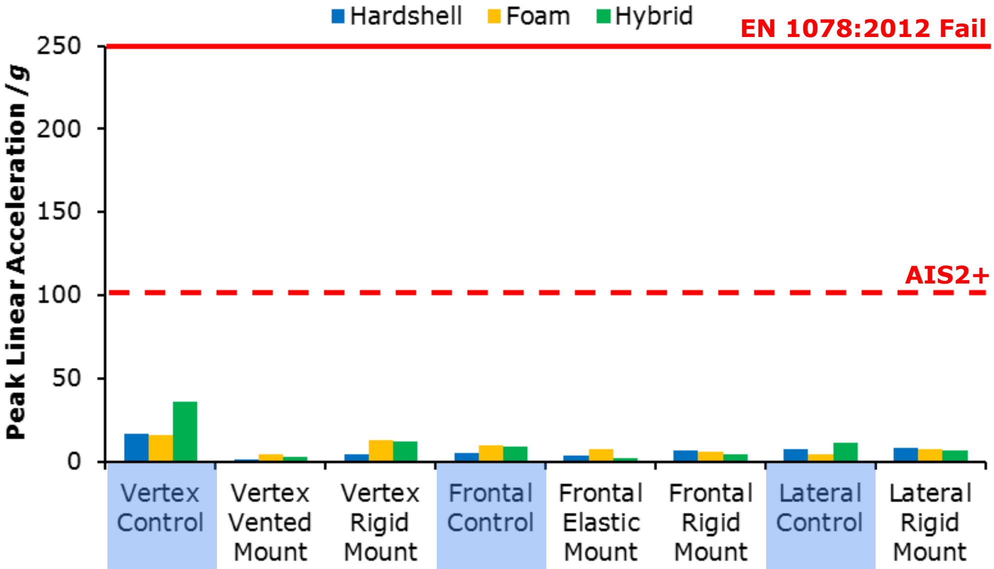


Figure 8: Comparison of peak linear accelerations experienced by all climbing helmet and camera combinations during oblique headform drop test impacts against the 250 *g* AIS5+ criteria (solid line) and 100 *g* AIS2+ injury thresholds (dashed line) specified by EN 1078:2012+A1:2012 and Newman (1980)

Key Finding 7: Climbing helmet-mounted cameras have a mixed effect on the risks of injury associated with angular velocities and accelerations during oblique impacts

When compared to the control test helmets, the addition of the helmet-mounted camera tested by this project was found to have a mixed effect on the injury risks associated with the angular velocities and accelerations experienced during oblique impacts to the helmet (Figure 9). All investigated helmet-mounted camera combinations may therefore be worn without exceeding injury thresholds associated with rotational head velocities and accelerations experienced during helmeted falls onto angled surfaces (i.e. falls onto angled floors or pendulum-like impacts with walls) for the specific impact mechanisms investigated by this project.

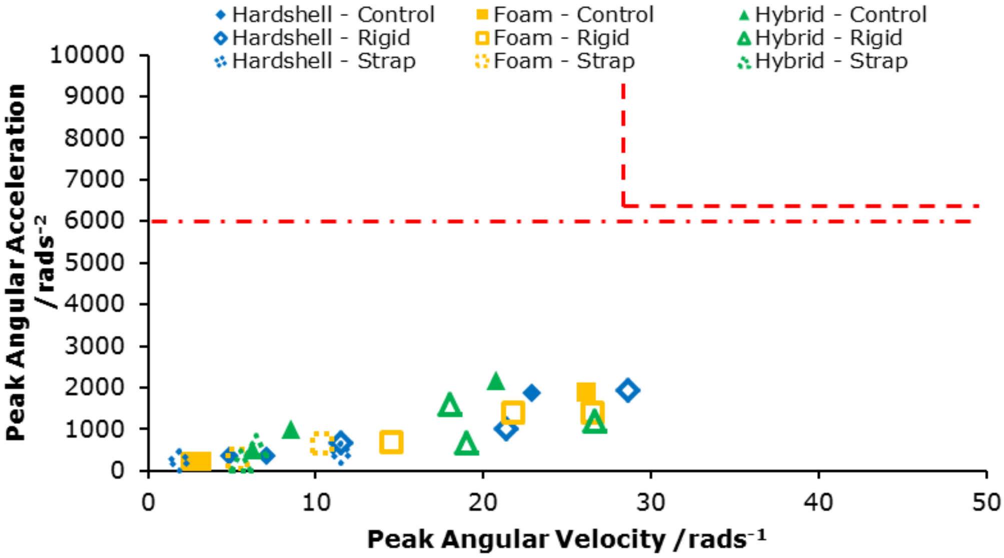


Figure 9: Comparison of the angular velocities and accelerations experienced by all climbing helmet and camera combinations during oblique drop test impacts against 50% probability of AIS2+ concussion thresholds (dashed-line adapted from Rowson et al. (2012), dot-dashed line adapted from Zhang et al. (2004))

Key Finding 8: Climbing helmet-mounted cameras detach during 40% of impacts

Overall 40% of all cameras detached from the climbing helmets tested throughout this project, with 40% of cameras detaching from the helmet in Work Package 1 (Table 3), 60% of cameras detaching from the helmet in Work Package 2 (Table 4) and 20% of cameras detaching from the helmet in Work Package 3 (Table 5). Across all Work Packages the greatest proportion of camera detachments was caused by either the mount unclipping from the sticky pad (27%) or the elasticated camera mount detaching from the helmet (7%). The camera was ejected from its protective casing in 13% of tests, whilst 4% of tests resulted in broken protective cases or mounts.

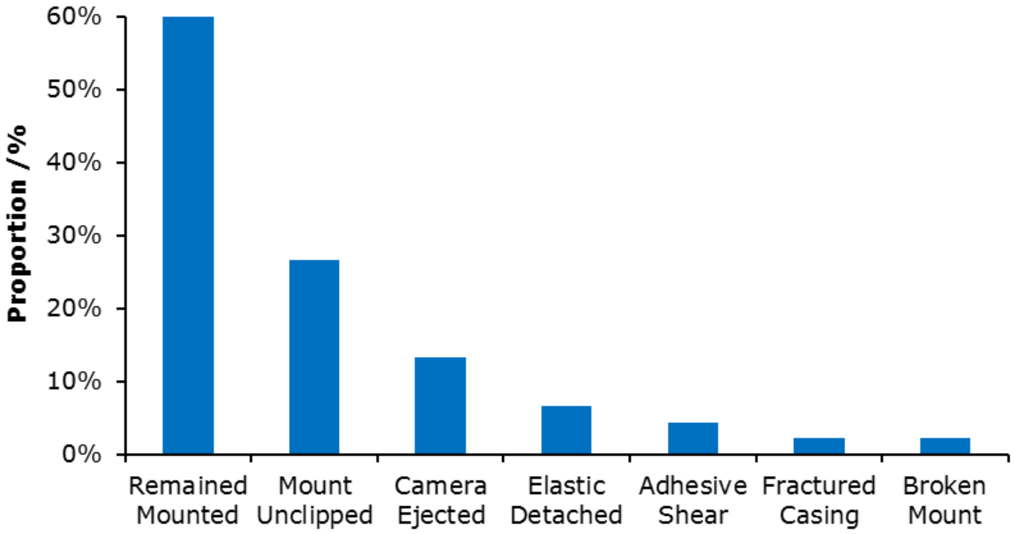


Figure 9: Mechanisms of climbing helmet camera detachment

Key Finding 9: Out-of-position tests increase the risks of injury during falling striker and linear impacts

Key Finding 9a: *Off-centre falling strikes to helmets increase the risks of injury associated with the forces transferred to the head during falling object strikes*

The off-centre falling striker test transferred an impact force of 14.6 kN to the vertex of the control hardshell helmet, exceeding the 10 kN threshold specified in EN 12492:2012. This suggests that the ability of the hardshell helmet to protect from falling object strikes is closely associated with impacts directly to the vertex of the head and that the wearer may be particularly vulnerable to a falling object strike from above that does not strike this particular area.

Key Finding 9b: *Greater helmet drop heights increase the risks of injury associated with all injury thresholds during linear lateral impacts*

The 2 m drop test on to the lateral impact location of the hardshell helmeted headform resulted in linear accelerations of 993*g*, HIC_{15} values of 10,380, angular velocities of 46 $rads^{-1}$ and angular accelerations of 6,823 $rads^{-2}$, considerably exceeding all published head injury thresholds. This suggests that the hardshell helmet may be unable to protect wearers during linear lateral impacts to the same level as during linear vertex impacts.

Key Finding 9c: *Front-mounted, rear-facing, climbing helmet-mounted cameras increase the risk of facial injury during linear frontal impacts*

Although no injury threshold was exceeded by the front-mounted, rear-facing, helmet camera and hardshell helmet combination, the camera mount broke off and impacted the headform face during testing, which could have serious consequences for the wearer, even during low energy impacts.

5 Limitations

The research methods adopted by this research are limited by a number of necessary assumptions and simplifications. No repeat tests were performed throughout this project, reducing confidence in the accuracy of the results. Despite this, no potentially anomalous results were identified across the results of this project, whilst the use of prospectively defined standardised testing methods mitigated the risks of methodological error.

The biomechanical response of the headform used throughout this project may not represent the response of the head during impact, whilst the lack of neck anchorage to the torso may also result in a less biofidelic impact response. Despite these issues, the key objective for this project was to compare the differences between the responses of the headform during helmet camera mounted and control helmet impacts. 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. Finally, the helmet impact test locations, the striker and helmeted headform drop heights and the striker and anvil impact surfaces assessed by this project may not represent those actually experienced during either falling object strikes or falls. Helmets specifically designed to pass EN 12492:2012 may therefore perform worse if impacted at non-tested locations, with greater impact energies or on surfaces inclined at different angles then those parameters investigated by this project.

6 Key Recommendations

Recommendation 1:

All climbing helmet-mounted camera combinations investigated by this project may be attached to all three evaluated helmet models, and at all three impact locations, without increasing injury risks beyond current legislative performance requirements or published injury thresholds.

Recommendation 2:

Front-mounted, rear-facing, helmet cameras are susceptible to breaking away from the helmet and impacting the face of the wearer, even during low energy impacts.

It must be noted that these recommendations and results are valid only for the impact configurations investigated by this project and that there are other conceivable scenarios where the mounting of a camera may compromise the safety of a helmet (as evidenced by Key Finding 9). It is important to note that these recommendations and results must also be taken in the context of the limitations of the approach adopted by this project. TRL therefore takes no responsibility for the actions of individuals, whilst wearing either a helmet or helmet-mounted camera, and advise that activity-specific risk assessments are always performed. Further testing should also be performed to establish the effects of any additional helmet and camera mounting configurations that do not correspond to those already evaluated by this project.

7 References

AAAM, 2008. *Abbreviated Injury Scale 2005, Update 2008.* Barrington, IL, USA: Association for the Advancement of Automotive Medicine (AAAM).

Bowie, W., Hunt, T. & Allen, H., 1988. Rock-climbing injuries in Yosemite National Park. *Western Journal of Medicine,* 149(2), p. 172.

Chinn, B. et al., 2001. *COST 327 Motorcycle safety helmets,* European Commission: Directorate General for Energy and Transport.

Cripton, P. A. et al., 2014. Bicycle helmets are highly effective at preventing head injury duringhead impact: Head-form accelerations and injury criteria forhelmeted and unhelmeted impacts. *Accident Analysis and Prevention,* Volume 70, pp. 1-7.

Lack, D., Sheets, Alison, Entin, J. & Christenson, D., 2012. Rock climbing rescues: causes, injuries, and trends in Boulder County, Colorado. *Wilderness & environmental medicine,* 23(3), pp. 223-230.

Locker, T., Chan, D. & Cross, S., 2004. Factors predicting serious injury in rock-climbing and non–rock-climbing falls. *Journal of Trauma and Acute Care Surgery,* 57(6), pp. 1321-1323.

McIntosh, A. S., Lai, A. & Schilter, E., 2013. Bicycle Helmets: Head Impact Dynamics in Helmeted and Unhelmeted Oblique Impact Tests. *Traffic Injury Prevention,* 14(5), pp. 501-508.

Mills, N. & Glichrist, A., 2008. Oblilque impact testing of bicycle helmets. *International Journal of Impact Engineering,* Volume 35, pp. 1075-1086.

Nelson, N. & McKenzie, L., 2009. Rock Climbing Injuries Treated in Emergency Departments in the U.S., 1990–2007. *American Journal of Preventive Medicine,* 37(3), pp. 195-200.

Newman, J. A., 1980. *Head injury criteria in automotive crash testing,* No. 801317: SAE Technical Paper.

Rowson, S. et al., 2012. Rotational head kinematics in football impacts: an injury risk function for concussion. *Annals of biomedical engineering,* 40(1), pp. 1-13.

Statista, 2015. *Unit sales of action cameras worldwide from 2010 to 2014 (in millions).* [Online]
Available at: http://www.statista.com/statistics/326898/worldwide-unit-sales-action-cams/
[Accessed 26 May 2015].

Zhang, L., King, Y. & King, A., 2004. A proposed injury threshold for mild traumatic brain injury. *Journal of biomechanical engineering,* 126(2), pp. 226-236.

Appendix A Detailed Methods

A.1 Existing Helmet Testing Standards

European Standard EN 12492:2012 guides current standardised testing procedures and baseline safety criteria for mountaineering helmets. EN 12492:2012 incorporates falling striker tests that use both flat and hemispherical strikers to assess the shock absorption performance of helmets at various impact locations. Impact locations include the vertex of the head and locations displaced 60° from the vertical axis toward the front, side and rear of the helmet. Hemispherical strikers (weighing 5 kg) are dropped from heights of 2 m for the vertex test, whilst flat strikers (weighing 5 kg) are dropped from 0.5 m heights for all other locations. Helmets are considered safe if the forces transmitted to the headform remain below 10 kN. Additional tests examine helmet penetration resistance, chinstrap strength and helmet slippage, but are outside the scope of this project.

Unfortunately, EN 12492:2012 simulates falling object strikes only and there is currently no international standard that evaluates climbing helmet safety through falling headform tests to simulate climbing falls. Current bicycle (EN 1078:2012+A1) and motorcycle (UN ECE Regulation 22.05) helmet European Standards may, however, be used as a guide for impact testing procedures and baseline safety criteria for climbing helmets during linear and oblique impacts. EN 1078:2012+A1 incorporates falling headform tests onto a flat anvil to assess the impact absorption performance of cycle helmets within a specified testing area. A standardised and instrumented helmeted headform is dropped in guided free-fall onto a flat steel anvil from heights of 1.5 m, with helmets considered to be safe if the linear accelerations experienced by the headform remain below 250g. The UN ECE Regulation 22.05 tests for projections and surface friction (method A) regulate the impact absorption performance of motorcycle helmet projections on inclined anvils. A standardised and instrumented helmeted headform is dropped in a guided free-fall from 2.9 m heights onto a steel bar anvil angled 15° to the vertical, with helmets considered to be safe if the longitudinal force measured by the anvil remains below 2,500 N and if the longitudinal impulse does not exceed 12.5 Ns.

A.2 Relevant Published Head Injury Thresholds

Aside from the previously described maximum injury thresholds required by the existing helmet testing standards, several established head injury thresholds were also used in this project. When considering linear head accelerations, Newman (1980) established a scale that related linear acceleration thresholds to Abbreviated Injury Scale (AIS) scores. Newman (1980) concluded that, whilst peak linear accelerations of >250 *g* are associated with an AIS5+ score, linear accelerations of >100 *g* are correlated with an AIS2+ score. This is further supported by Chinn et al. (2001), who determined that 15 ms head injury criteria (HIC)[1] values of 1000 were associated with AIS2+ scores. When considering the angular velocities and accelerations of the head, two research studies, using reconstructed and *in-vivo* American Football accident data, were used to determine best estimates for 50% probability thresholds for AIS2+ concussion injuries (i.e. a loss of consciousness for <1 hour) (Zhang, et al., 2004; Rowson, et al., 2012).

[1] HIC values are determined as a function of the integral of the accelerations, with respect to time, to provide values representing the average acceleration over the most critical part of the acceleration pulse.

A.3 Helmet Designs

The majority of modern climbing helmets fit into one of three categories (hardshell, foam or hybrid), which can be separated by their unique mechanical characteristics. Hardshell helmets are typically characterised by stiff, heavy polycarbonate shells and adjustable internal suspension cradles constructed from flexible webbing material. Foam helmets feature very thin polycarbonate shells that are fully integrated with lightweight moulded expanded polystyrene (EPS) inner liners. Finally, hybrid helmets are designed to have a combination of EPS inner liners surrounded by thinner and lighter FRP shells. To ensure a representative sample, the helmets selected for assessment by this project were the Petzl VERTEX® VENT (hardshell), Petzl METEOR (foam) and Petzl ELIOS (hybrid). Below is a detailed description of these helmets.

A.3.1 Petzl VERTEX® Vent

This 455 g hardshell helmet is constructed from a thick Acrylonitrile Butadiene Styrene (ABS) shell and a six-point adjustable suspension cradle system. Free space is created at the vertex by a pair of crossed overhead polyester webbing straps sewn together at a crossing point. Apart from a thin region of closed cell foam (CCF) lining the inside of the helmet vertex, no further foam materials were mounted inside the helmet. Externally the helmet has a number of sliding ventilation holes and accessory attachment mounts. Energy absorption in this helmet appears to be principally provided by the deformation of the ABS shell, webbing straps and plastic strap mounts.

A.3.2 Petzl METEOR

This 225 g foam helmet is constructed from a thin polycarbonate shell, EPS inner liner and adjustable polyester webbing straps. The moulded EPS inner liner, which appears to provide much of the structural rigidity for the helmet, fully surrounds the head and was found to be thicker at the vertex than the helmet peripheries. A comfort liner of open cell foam (OCF) was affixed inside the top of the helmet with Velcro. Externally the helmet has a number of permanent ventilation holes, accessory attachment mounts and two adjustable headband buttons. Energy absorption in this helmet appears to be principally provided by the deformation of the EPS inner liner.

A.3.3 Petzl ELIOS

This 330 g hybrid hardshell/foam helmet is constructed from a medium thick ABS shell, a moulded EPS inner liner and a six-point polyester adjustable suspension cradle system. The EPS inner liner surrounds the upper two-thirds of the helmet, an OCF comfort liner was affixed inside the top of the helmet with Velcro and a thin CCF strip lined the inside of the helmet headband. Externally the helmet has a number of sliding ventilation holes, accessory attachment mounts and an adjustable headband button. Energy absorption in this helmet appears to be jointly provided by the deformation of the ABS shell, webbing straps and EPS inner liner.

A.4 Impact Test Locations

Three impact locations, based on EN 12492:2012 requirements and current BBC helmet camera mounting practice, were evaluated by this project. These locations included the vertex of the helmet and frontal and lateral locations angled at 30° from the transverse plane and toward the front and side of the helmet (Figure 10, impact points V, F and L). Impact locations were marked for testing using the TRL certified laser alignment table.

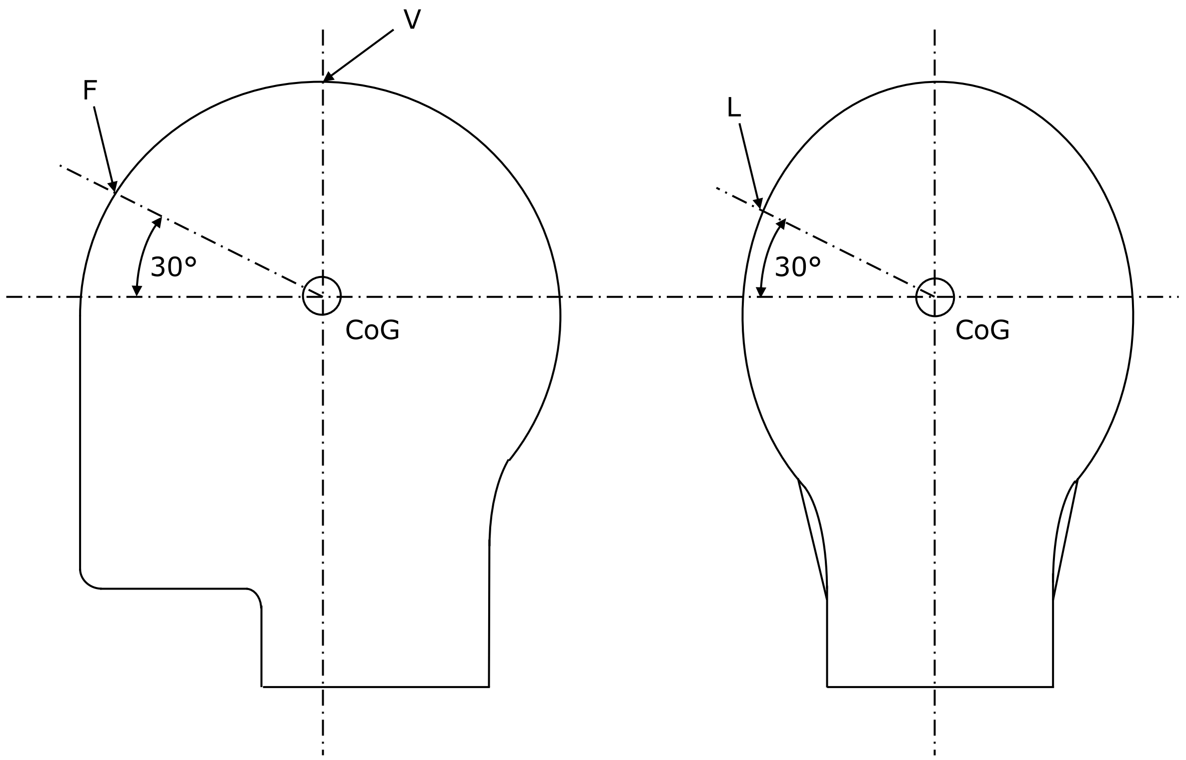


Figure 10: Impact points on helmeted headform
(V, vertex impact point; F, frontal impact point; L, lateral impact point; CoG, centre of gravity)

A.5 Sample Preparation

A total of 75 climbing helmets were tested by this project. For each helmet category, eight medium sized helmets (to fit the EN 960:2006 compliant 575 mm circumference headform) were tested. All helmet samples were submitted for testing in the condition they were offered for sale, including any helmet shell apertures, accessory attachments and comfort padding. No pre-conditioning was performed for the helmet. All test helmets were anonymised by taping over the manufacturer name.

The shock and impact absorption performance of all three categories of climbing helmet were assessed for each Work Package across all three impact locations using five camera mounting options and three control tests (Table 1 and Table 2, Appendix B). Using these helmet-mounted camera testing configurations, a GoPro Hero4 camera was housed in a Skeleton HD impact protection case and mounted to the helmet at the impact location using either rigid camera mounts, elasticated straps or adjustable polyester straps, as specified. No helmet-mounted cameras were required for the control test helmets.

To allow representative curing times, all rigid mounts were adhered to the helmet at least one day prior to testing. As all adjustable polyester straps were looped through the open ventilation holes, the sliding ventilation holes of all helmets were left fully open.

A.6 Headforms

All tests used an instrumented EN 960:2006 compliant 575 mm circumference headform (4.7 kg mass).

A.7 Helmet Adjustment

All climbing helmets were adjusted to the headform size and positioned according to the manufacturer's instructions. A load of 50 N was applied to the vertex of the helmet to adjust the helmet such that there was contact between the inner surface of the helmet and the headform vertex. The retention system was then adjusted under the chin of the headform and, as defined in the standards, any strapping tightened as much as possible.

A.8 Work Package 1: Falling Striker Testing Procedure

A.8.1 Method of Approach

The shock absorbing performance of the three climbing helmet categories was assessed across three impact test locations using a total of five camera mounting options and three control tests. European Standard EN 12492:2012 incorporates falling striker impact tests, using both flat and hemispherical strikers, to evaluate the shock absorbing performance of mountaineering helmets at various impact locations. EN 12492:2012 was therefore adapted by this Work Package to guide the testing procedures applied by this study. The following sections provide further detail on this procedure.

A.8.2 Strikers

Two 5 kg flat and hemispherical steel strikers were used in this Work Package. The flat striker had a 130 mm diameter striking face, with the edge of its circumference radiused to 2 mm. The hemispherical striker had a hemispherical striking face of radius 50 mm.

A.8.3 Guidance System

A wire guidance system with a steel base provided the means for the striker to be dropped in a guided free-fall. This system was designed to ensure that the striker:

- Was positioned above the headform so its central axis coincided with the central vertical axis of the force transducer
- Impacted the camera or helmet impact location such that the line of impact acted through the centre of gravity of the helmeted headform and camera assembly
- Impacted the camera or helmet impact location with an initial impact speed of ≥95 % of that which would theoretically be obtained for a free-fall

A.8.4 Helmeted Headform Positioning

The helmeted headform was mounted on a customised solid steel base that allowed the helmeted headform to be repositioned for testing at all three impact locations. For the control test helmets, the helmeted headform was positioned such that the test helmet was impacted at the desired impact test location with the normal reaction force acting through the headform centre of gravity. For the camera mounted helmets, the camera was positioned on the helmeted headform such that a “worst case scenario” impact on the camera (as judged by the investigator) was performed.

A.8.5 Instrumentation

Initial impact velocities were calculated using an infra-red light gate located just above the point of impact between the helmeted headform and striker. A non-inertial uniaxial force transducer was firmly attached to the customised base and arranged such that its sensitive axis coincided with the vertical axis of the helmeted headform and the central axis of the striker. The acceleration and velocity of the striker was analysed by a uniaxial accelerometer located on the striker carriage.

A.8.6 Striker Drop Test Procedure

The hemispherical striker was raised to a height of 2 m before being dropped in a guided free-fall onto the vertex of the helmet, whilst the flat striker was raised to a height of 0.5 m before also being dropped in a guided free-fall onto the frontal and lateral impact test locations.

A.9 Work Package 2: Linear Headform Drop Testing Procedure

A.9.1 Method of Approach

The linear impact absorbing performance of the three climbing helmet categories was assessed across three impact test locations using a total of five camera mounting options and three control tests. European Standard EN 1078:2012+A1:2012 incorporates helmeted headform drop tests that impact the helmet against a flat anvil to assess the impact performance of bicycle helmets. EN 1078:2012+A1:2012 and EN 12492:2012 were therefore adapted by this Work Package to guide the test procedures applied by this study. The following sections provide further detail on these procedures.

A.9.2 Anvil

A flat steel anvil with a 130 mm diameter impact face and 2 mm radiused circumference was used in this Work Package.

A.9.3 Guidance System

A drop carriage rail guidance system with a steel base provided the means for the helmeted headform to be dropped in a guided free-fall. This system was designed to ensure that the helmeted headform and camera assembly:

- Were positioned above the anvil such that their centre of gravity and the impact location coincided with the central vertical axis of the anvil
- Impacted the camera or helmet impact location with an initial impact speed of ≥95 % of that which would theoretically be obtained for a free-fall

A.9.4 Helmeted Headform Positioning

The test helmet was mounted in the drop carriage to allow the helmeted headform to be repositioned for testing at all three impact locations. For the control test helmets, the helmeted headform was positioned so that the test helmet was impacted at the desired impact test location with the normal reaction force acting through the headform centre of gravity. For the camera mounted helmets, the camera was positioned on the helmeted headform such that a “worst case scenario” impact on the camera (as judged by the investigator) was performed.

A.9.5 Instrumentation

Initial impact velocities were calculated using an infra-red light gate located just above the point of impact between the helmeted headform and anvil. The linear accelerations and angular velocities experienced at the centre of gravity (CoG) of the headform were recorded by three uniaxial accelerometers and three uniaxial angular rate sensors during impact. These sensors were mounted to a 0.15 kg customised adapter that ensured the sensor axes were coincident and intersected at the headform CoG. The sensor axes were defined as follows:

- X-axis: perpendicular to the headform frontal plane
- Y-axis: perpendicular to the headform sagittal plane
- Z-axis: perpendicular to the headform transverse plane

A.9.6 Headform Drop Test Procedure

The helmeted headforms were raised to drop heights of 2 m for the vertex of the helmet impact test location and 0.5 m for the frontal and lateral impact test locations before being dropped onto the flat steel anvil in a guided free-fall.

A.10 Work Package 3: Oblique Headform Drop Testing Procedure

A.10.1 Method of Approach

The oblique impact absorbing performance of the three climbing helmet categories was assessed across three impact test locations using a total of five camera mounting options and three control tests. UN ECE Regulation 22.05 tests for projections and surface friction (method A) incorporates helmeted headform drop tests that impact the helmet against an angled steel bar anvil to evaluate the shock absorbing performance of motorcycle helmets. UN ECE Regulation 22.05 and EN 12492:2012 were therefore adapted by this Work Package to guide the test procedures applied by this study. The following sections provide further detail on these procedures.

A.10.2 Anvil

A steel bar anvil, angled at 15° to the vertical and secured to a steel frame to allow for fore-and-aft alignment, was used in this Work Package. The anvil was 200 mm wide and consisted of a series of five horizontal bars located 15 mm apart. Each bar was made from a steel strip of height 6 mm and width 25 mm, with its uppermost edge radiused to 1 mm and the lower 15 mm of its face chamfered to an angle of 15° so that, as mounted, the upper edge of each bar was fully exposed from above. Each bar was then case-hardened to a depth of approximately 0.5 mm.

A.10.3 Guidance System

A drop carriage rail guidance system with a steel base provided the means for the helmeted headform to be dropped in a guided free-fall. This system was designed to ensure that the helmeted headform and camera assembly:

- Were positioned above the anvil such that the helmet or camera impact location coincided with the centre point of the anvil
- Impacted the camera or helmet impact location with an initial impact speed of ≥95 % of that which would theoretically be obtained for a free-fall

A.10.4 Helmeted Headform Positioning

The test helmet was mounted on the drop carriage to allow the helmeted headform to be repositioned for testing at all three impact locations. For the control test helmets, the helmeted headform was positioned such that the test helmet was first impacted at the desired impact location. For camera mounted helmets, the camera was positioned on the helmeted headform such that a "worst case scenario" impact on the camera (as judged by the investigator) was performed.

A.10.5 Instrumentation

Initial impact velocities were calculated using an infra-red light gate located just above the point of impact between the helmeted headform and anvil. A non-inertial tri-axial force transducer was securely attached between the anvil and steel frame and positioned to record both the longitudinal forces experienced by the anvil. The linear accelerations and angular velocities experienced at the headform CoG were recorded as previously described in Appendix A.9.5.

A.10.6 Headform Drop Test Procedure

The helmeted headforms were raised to drop heights of 2 m for the vertex of the helmet impact test location and 0.5 m for the frontal and lateral impact test locations before being dropped onto the angled anvil in a guided free-fall.

A.11 Out-of-Position Testing Procedure

Three "out-of-position" impact tests were also performed to investigate the effects of non-standardised impacts to the helmet (i.e. test configurations not compliant with the helmet testing standards). For consistency, all tests were performed on the hardshell helmet and included an off-centre falling striker impact to the top of the helmet, a lateral linear headform drop test with the helmeted headform dropped from a height of 2 m and a frontal linear headform drop test performed with a front-mounted, rear-facing, helmet-mounted camera. The testing procedures for the off-centre falling striker test replicated those in Appendix A.8. The testing procedures for the linear headform drop tests performed using 2 m drop test heights on to the lateral impact test location and using a front-mounted, rear-facing, helmet camera replicated those in Appendix A.9.

A.12 Data Processing

High speed video was captured for all tests at a frame rate of 1,000 frames per second. 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. Data collected in this project included:

- Work Package 1:
    - Initial impact velocity [v_0] from the infra-red light gate
    - Impact force [F] against time from the uniaxial force transducer
    - Striker acceleration [a] against time from the uniaxial accelerometer
- Work Package 2:
    - Initial impact velocity [v_0] from the infra-red light gate
    - X-axis headform acceleration [a_x] against time from the X-axis uniaxial accelerometer

    - Y-axis headform acceleration [a_y] against time from the Y-axis uniaxial accelerometer
    - Z-axis headform acceleration [a_z] against time from the Z-axis uniaxial accelerometer
    - X-axis headform angular velocity [ω_x] against time from the X-axis uniaxial angular rate sensor
    - Y-axis headform angular velocity [ω_y] against time from the Y-axis uniaxial angular rate sensor
    - Z-axis headform angular velocity [ω_z] against time from the Z-axis uniaxial angular rate sensor
- Work Package 3:
    - Initial impact velocity from the infra-red light gate
    - Initial impact velocity [v_0] from the infra-red light gate
    - X-axis headform acceleration [a_x] against time from the X-axis uniaxial accelerometer
    - Y-axis headform acceleration [a_y] against time from the Y-axis uniaxial accelerometer
    - Z-axis headform acceleration [a_z] against time from the Z-axis uniaxial accelerometer
    - X-axis headform angular velocity [ω_x] against time from the X-axis uniaxial angular rate sensor
    - Y-axis headform angular velocity [ω_y] against time from the Y-axis uniaxial angular rate sensor
    - Z-axis headform angular velocity [ω_z] against time from the Z-axis uniaxial angular rate sensor
    - X-axis anvil impact force [F_x] against time from the X-axis of the tri-axial force transducer
    - Y-axis anvil impact force [F_y] against time from the Y-axis of the tri-axial force transducer
    - Z-axis anvil impact force [F_z] against time from the Z-axis of the tri-axial force transducer

The following data processing was performed for each Work Package:

- Work Package 1:
    - Initial impact energy [KE_0] = $½.m.v_0^2$
    - Impact impulse [J] = $\int F.dt$
    - *Initial bias was corrected for by removing the mean of the first 1000 data points prior to impactor release*
    - *Start (t_0) and finish (t_{final}) times were manually defined*
    - *Data was zeroed using the mean of 200 data points before* t_0
    - *All data was filtered at channel frequency class (CFC) 1000*
    - *All values were calculated for the period* t_0 *to* t_{final}
- Work Package 2:
    - Initial impact energy [KE_0] = $½.m.v_0^2$
    - Resultant linear acceleration [a] = $\sqrt{(a_x^2 + a_y^2 + a_z^2)}$
    - X-axis linear velocity [v_x] = $\int a_x.dt$
    - Y-axis linear velocity [v_y] = $\int a_y.dt$
    - Z-axis linear velocity [v_z] = $\int a_z.dt$
    - Resultant linear velocity [v] = $\sqrt{(v_x^2 + v_y^2 + v_z^2)}$

- Resultant angular velocity [ω] = $|\omega_x|+|\omega_y|+|\omega_z|$
- Resultant angular acceleration [α] = $d\omega/dt$
- Head injury criterion (15ms) [HIC_{15}] = $\left\{(t_2-t_1)\left[\left(\frac{1}{t_2-t_1}\right)\int_{t_1}^{t_2} a.dt\right]^{2.5}\right\}_{max}$
- *Initial bias was corrected for by removing the mean of the first 1000 data points prior to impactor release*
- t_0 *was defined as the first point that* a *exceeded 3 g*
- t_{final} *was manually defined*
- *Data was zeroed using the mean of 200 data points before* t_0
- *All data was filtered at CFC 1000*
- *X, Y and Z-axis angular velocity channels were further filtered at CFC 60*
- *All values were calculated for the period* t_0 *to* t_{final}

* Work Package 3:
  - Initial impact energy [KE_0] = ½.m.v_0^2
  - Resultant linear acceleration [a] = $\sqrt{(a_x^2 + a_y^2 + a_z^2)}$
  - X-axis linear velocity [v_x] = $\int a_x.dt$
  - Y-axis linear velocity [v_y] = $\int a_y.dt$
  - Z-axis linear velocity [v_z] = $\int a_z.dt$
  - Resultant linear velocity [v] = $\sqrt{(v_x^2 + v_y^2 + v_z^2)}$
  - Resultant angular velocity [ω] = $|\omega_x| + |\omega_y| + |\omega_z|$
  - Resultant angular acceleration [α] = $d\omega/dt$
  - Longitudinal force [F_L] = $\sqrt{(F_x^2 + F_y^2)}$
  - Longitudinal impulse [J_L] = $\int F_L.dt$
  - Resultant force [F_T] = $\sqrt{(F_x^2 + F_y^2 + F_z^2)}$
  - Head injury criterion (15ms) [HIC_{15}] = $\left\{(t_2-t_1)\left[\left(\frac{1}{t_2-t_1}\right)\int_{t_1}^{t_2} a.dt\right]^{2.5}\right\}_{max}$
  - *Initial bias was corrected for by removing the mean of the first 1000 data points prior to impactor release*
  - t_0 *was defined as the first point that* F_T *exceeded 25 N*
  - t_{final} *was manually defined*
  - *Data was zeroed using the mean of 200 data points before* t_0
  - *All data was filtered at CFC 1000*
  - *X, Y and Z-axis angular velocity channels were further filtered at CFC 60*
  - *All values were calculated for the period* t_0 *to* t_{final}

A.13 Data Analysis

Results compared the safety performances of the camera mounted helmets both against the control helmets and against legislative performance criteria (i.e. minimum levels of protection specified by European standards and regulations) and selected published injury thresholds (i.e. additional criteria that relate to a 50% risk of either a simple linear fracture of the skull or a loss of consciousness for <1 hour).

A.13.1 Work Package 1: Falling Striker Tests

Results for each test include the initial impact kinetic energy, the peak impact force, the peak impact impulse, the proportion of cameras observed to detach from the helmet and the camera detachment mechanism.

A.13.2 Work Package 2: Linear Headform Drop Tests

Results for each test include the initial impact kinetic energy, the peak resultant linear acceleration, the head injury criterion (HIC15), the peak resultant angular velocity, the peak resultant angular acceleration, the proportion of cameras observed to detach from the helmet and the camera detachment mechanism.

A.13.3 Work Package 3: Oblique Headform Drop Tests

Results for each test include the initial impact kinetic energy, the peak resultant linear acceleration, the head injury criterion (HIC15), the peak resultant angular velocity, the peak resultant angular acceleration, the peak longitudinal force, the peak longitudinal impulse, the proportion of cameras observed to detach from the helmet and the camera detachment mechanism.

A.13.4 Out-of-Position Tests

Results for the off-centre falling striker test replicated those reported above in Appendix A.13.1. Results for the linear headform drop tests performed using a 2 m drop test height on to the lateral impact location and using a front-mounted, rear-facing, helmet camera replicated those reported above in Appendix A.13.2.

Appendix B Testing Matrices

Table 1: Illustration of climbing helmet camera mounting options for each test impact location

Impact Location	Helmet Camera Mounting Option	Illustration
Vertex	Rigid Mount	
Vertex	Adjustable Vented Helmet Strap	
Frontal	Rigid Mount (Forward Facing)	
Frontal	Elasticated Strap	
Lateral	Rigid Mount	

Table 2: Testing matrix for Work Packages 1, 2 and 3

Test #	Helmet Type	Impact Location	Helmet Camera Mounting Option
1	Hard Shell	Vertex	No Camera (Control)
2	EPS Foam	Vertex	No Camera (Control)
3	Hybrid	Vertex	No Camera (Control)
4	Hard Shell	Vertex	Rigid Mount
5	EPS Foam	Vertex	Rigid Mount
6	Hybrid	Vertex	Rigid Mount
7	Hard Shell	Vertex	Adjustable Vented Helmet Strap
8	EPS Foam	Vertex	Adjustable Vented Helmet Strap
9	Hybrid	Vertex	Adjustable Vented Helmet Strap
10	Hard Shell	Frontal	No Camera (Control)
11	EPS Foam	Frontal	No Camera (Control)
12	Hybrid	Frontal	No Camera (Control)
13	Hard Shell	Frontal	Rigid Mount (Forward Facing)
14	EPS Foam	Frontal	Rigid Mount (Forward Facing)
15	Hybrid	Frontal	Rigid Mount (Forward Facing)
16	Hard Shell	Frontal	Elasticated Strap
17	EPS Foam	Frontal	Elasticated Strap
18	Hybrid	Frontal	Elasticated Strap
19	Hard Shell	Lateral	No Camera (Control)
20	EPS Foam	Lateral	No Camera (Control)
21	Hybrid	Lateral	No Camera (Control)
22	Hard Shell	Lateral	Rigid Mount
23	EPS Foam	Lateral	Rigid Mount
24	Hybrid	Lateral	Rigid Mount

Appendix C Data Tables

Table 3: Work Package 1 results

Helmet Category	Impact Location	Camera Mount	Impact Energy /J	Peak Force /kN	Camera Status
Hardshell	Vertex	Control	91.7	7.9	-
Foam	Vertex	Control	91.7	5.7	-
Hybrid	Vertex	Control	92.3	7.8	-
Hardshell	Vertex	Rigid Mount	90.5	4.8	U
Foam	Vertex	Rigid Mount	90.5	4.3	U,E
Hybrid	Vertex	Rigid Mount	89.6	5.8	U
Hardshell	Vertex	Vented Strap	89.9	4.6	U
Foam	Vertex	Vented Strap	89.6	3.6	U
Hybrid	Vertex	Vented Strap	90.2	5.3	U,E
Hardshell	Frontal	Control	23.4	5.7	-
Foam	Frontal	Control	22.6	3.6	-
Hybrid	Frontal	Control	22.2	6.0	-
Hardshell	Frontal	Rigid Mount	23.1	3.8	M
Foam	Frontal	Rigid Mount	23.2	2.6	M
Hybrid	Frontal	Rigid Mount	24.3	3.8	M
Hardshell	Frontal	Elastic Strap	23.7	4.7	M
Foam	Frontal	Elastic Strap	23.2	3.2	M
Hybrid	Frontal	Elastic Strap	23.1	4.5	M
Hardshell	Lateral	Control	22.2	6.2	-
Foam	Lateral	Control	22.3	2.8	-
Hybrid	Lateral	Control	24.4	3.5	-
Hardshell	Lateral	Rigid Mount	24.1	2.2	M
Foam	Lateral	Rigid Mount	23.5	2.3	M
Hybrid	Lateral	Rigid Mount	23.7	2.3	M

(Abbreviations: E, camera ejected from impact protection case; M, camera remained mounted to helmet; U, impact protection case and camera unclipped from helmet)

Table 4: Work Package 2 results

Helmet Category	Impact Location	Camera Mount	Impact Energy /J	Peak Linear Acceleration /g	Head Injury Criterion (HIC_{15})	Peak Angular Velocity /rads^{-1}	Peak Angular Acceleration /rads^{-2}	Camera Status
Hardshell	Vertex	Control	95.0	193.9	817.8	5.7	1481.0	-
Foam	Vertex	Control	95.0	150.0	876.6	5.5	1044.0	-
Hybrid	Vertex	Control	94.7	189.5	906.1	7.8	1539.6	-
Hardshell	Vertex	Rigid Mount	94.4	51.5	108.4	22.0	1850.5	U,E
Foam	Vertex	Rigid Mount	93.8	56.3	73.9	11.7	1808.2	U
Hybrid	Vertex	Rigid Mount	94.4	58.7	62.3	28.3	1849.0	U,E
Hardshell	Vertex	Vented Strap	95.6	48.9	40.2	5.7	1011.9	U,F,E
Foam	Vertex	Vented Strap	94.7	68.3	176.6	15.0	923.7	B
Hybrid	Vertex	Vented Strap	95.0	79.4	128.1	22.0	1003.6	U,E
Hardshell	Frontal	Control	22.7	189.1	473.7	20.5	4466.7	-
Foam	Frontal	Control	22.3	63.1	120.7	11.7	2231.1	-
Hybrid	Frontal	Control	23.0	198.7	687.2	20.5	4535.3	-
Hardshell	Frontal	Rigid Mount	23.2	39.3	17.6	30.4	2340.5	S
Foam	Frontal	Rigid Mount	22.6	22.9	10.8	19.2	2181.8	U
Hybrid	Frontal	Rigid Mount	22.9	57.3	102.9	27.3	3347.2	M
Hardshell	Frontal	Elastic Strap	23.0	23.4	146.5	29.8	2698.9	M
Foam	Frontal	Elastic Strap	23.3	30.8	27.8	33.7	3761.5	M
Hybrid	Frontal	Elastic Strap	22.7	38.2	35.7	32.6	3646.2	M
Hardshell	Lateral	Control	21.1	145.4	234.2	35.3	5946.6	-
Foam	Lateral	Control	21.4	64.5	95.8	26.4	4067.8	-
Hybrid	Lateral	Control	21.1	62.2	87.6	42.6	6031.5	-
Hardshell	Lateral	Rigid Mount	21.7	34.0	22.2	41.7	4468.4	M
Foam	Lateral	Rigid Mount	22.6	21.8	11.0	13.9	2003.2	S
Hybrid	Lateral	Rigid Mount	21.2	33.7	10.4	36.2	2309.9	M

(Abbreviations: B, camera mount broke; E, camera ejected from impact protection case; F, impact protection casing fractured; M, camera remained mounted to helmet; S, rigid camera mount sheared away from the helmet at the adhesive interface; U, impact protection case and camera unclipped from helmet)

Table 5: Work Package 3 results

Helmet Category	Impact Location	Camera Mount	Impact Energy /J	Peak Linear Acceleration /g	Head Injury Criterion (HIC_{15})	Peak Angular Velocity /rads^{-1}	Peak Angular Acceleration /rads^{-2}	Peak Longitudinal Force /kN	Peak Longitudinal Impulse /Ns	Camera Status
Hardshell	Vertex	Control	93.2	16.6	7.1	22.9	1848.1	0.35	4.6	-
Foam	Vertex	Control	92.9	15.9	5.2	26.1	1902.5	0.33	3.9	-
Hybrid	Vertex	Control	94.1	35.8	18.9	20.8	2160.9	0.37	6.0	-
Hardshell	Vertex	Rigid Mount	97.2	4.7	0.3	11.5	657.3	0.90	7.3	M
Foam	Vertex	Rigid Mount	90.2	12.8	0.8	14.5	687.8	0.42	4.9	M
Hybrid	Vertex	Rigid Mount	95.9	12.2	0.7	18.1	1593.7	0.48	6.3	M
Hardshell	Vertex	Vented Strap	93.2	1.3	0.0	1.9	231.6	0.31	1.9	M
Foam	Vertex	Vented Strap	95.9	4.6	0.2	10.4	670.6	0.36	4.7	M
Hybrid	Vertex	Vented Strap	94.4	3.2	0.0	6.5	602.0	0.60	6.2	M
Hardshell	Frontal	Control	22.6	5.2	0.6	7.1	348.1	0.13	2.3	-
Foam	Frontal	Control	22.9	9.7	2.4	2.5	233.8	0.14	2.2	-
Hybrid	Frontal	Control	22.6	9.4	1.5	6.3	494.1	0.21	2.7	-
Hardshell	Frontal	Rigid Mount	22.6	7.0	1.1	21.4	999.0	0.44	6.7	M
Foam	Frontal	Rigid Mount	22.6	6.2	0.9	21.8	1388.1	0.35	5.0	M
Hybrid	Frontal	Rigid Mount	22.7	4.5	0.4	19.0	661.1	0.46	7.0	M
Hardshell	Frontal	Elastic Strap	22.2	4.0	0.2	11.0	286.3	0.46	6.9	D
Foam	Frontal	Elastic Strap	22.9	7.9	0.8	5.3	274.6	0.45	6.7	D
Hybrid	Frontal	Elastic Strap	23.9	2.1	0.0	5.6	226.5	0.22	3.0	D
Hardshell	Lateral	Control	21.5	7.4	0.4	4.9	365.9	0.24	2.8	-
Foam	Lateral	Control	20.8	4.4	0.3	3.2	238.0	0.06	1.0	-
Hybrid	Lateral	Control	21.8	11.1	1.7	8.6	1010.8	0.20	1.5	-
Hardshell	Lateral	Rigid Mount	21.6	8.4	1.4	28.6	1910.3	0.43	7.0	M
Foam	Lateral	Rigid Mount	22.1	7.7	1.6	26.5	1393.4	0.44	5.3	M
Hybrid	Lateral	Rigid Mount	21.7	7.0	1.2	26.6	1191.3	0.44	5.8	M

(Abbreviations: M, camera remained mounted to helmet; D, camera mount, impact protection case and camera detached from helmet)