ABSTRACT

Criticisms of bicycle helmet design are reviewed, and changes in the design since the 1990’s explored. Finite Element Analysis is used to model the impact of a generic helmet on flat and kerbstone anvils. The performance of current helmets was investigated using oblique impacts, in which the liner and rotational acceleration of a headform, fitted with a compliant scalp and a wig, were measured. Most of the design criticisms are shown to be invalid. The peak values of rotational acceleration were of the order of 5 krad s^{-2}. However the coverage of the side of the head is not optimal.

Keywords: bicycle, helmet, impact, materials, protection

LAST PAPER DEALS WITH HELMET DESIGN and performance issues, but not the interpretation of trends in bicycle accident statistics, which are reviewed by Thompson et al (2003). It is the initial part of a larger programme to improve the performance of bicycle helmets. The two main reasons for the analysis and testing, described in this paper, are to investigate:

Recent comments on bicycle helmet performance

In spite of the large number of papers written by medics, showing the efficiency of bicycle helmets in reducing head injuries, there are several campaigners against the compulsory use of cycle helmets, who argue that helmets are ineffective. Burdett (2002), of the Ontario Coalition for Better Cycling, argued that:

a) headforms lack soft tissue, so the force vs. deflection response of the helmet differs from that in helmet impact tests.

b) vents in cycle helmets lead to excessive pressures on the skull.

c) ‘the helmet’s liner is made of stiff foam and requires a certain minimum force before it starts to crush. Until this minimum is reached, the head must absorb the impact. This means that, whilst helmets are designed to limit the impact (deceleration) to a just sub-lethal level, they won’t reduce it much below that. In these cases ‘sub-lethal’ translates into anything from a very bad concussion to a coma.’

Curnow (2003) argued that the design of helmets reflects a discredited theory of brain injury (that injuries are caused by peak linear acceleration). He is correct in that the standards (EN 1078, Snell, CPSC) do not have oblique impact tests, in which the headform rotational acceleration is measured. However the premise, that the majority of bicyclists’ head injuries are due to rotational acceleration, is not proven. He argues that epidemiological studies do not distinguish between skull fractures and injuries caused by angular acceleration; consequently they do not demonstrate the efficiency of helmets in preventing head injury.

Franklin (2000) also criticised the lack of oblique impact tests in helmet standards, writing ‘there does not appear to be research evidence that cycle helmets are effective in mitigating angular impacts. Henderson (1995) is himself critical of vertical drop tests, noting that the solid headform used for standards approval does not mimic the deformable characteristics of the human head.’ ‘McIntosh and Dowdell (1991) appear to have found no cases of helmeted cyclists surviving crashes where the
equivalent impact velocity was greater than 20 km/h.’ However Australian helmets in 1991 differ radically (some had thick, hard shells, while some with soft shells fractured) from those of 2003. The vertical impact velocities of up to 20 km/h, in their laboratory impact tests which reproduced helmet damage, do not infer that a cyclist, who is travelling at more than 20 km/h, has a high risk of a fatal head injury.

A BMJ booklet (1999) states: ‘Cycle helmets are designed to protect the head during a low speed impact, e.g. 20 km/h, such as would occur in a fall to the ground from a bicycle. It is likely that most of the 183 UK cyclist deaths recorded in 1997 would have resulted from velocities and energies in excess of the average cycle helmet’s ability to prevent the tragic outcome.’ However, there is no research evidence to support the 2nd statement; we do not know how the fraction of the cyclists who wore helmets, or the crash circumstances.

It is possible to check the validity of most of these statements by carrying out experiments.

Recent changes in bicycle helmet design.

The design of helmets has changed markedly since Mills’ (1990) tests on helmets that met BS 6863 (1987). The standard has changed to BSEN 1078 (1977). Current helmets have much larger ventilation slots, extensions at the front and rear for streamlining, and sometimes a non-smooth external profile. The only recent paper with any experimental testing of cycle helmets is Hui and Yu (2002). Figure 1 compares large ventilation holes in a Giro Targa helmet, with smaller holes in a 1994 helmet. 1980’s helmets had even smaller vents.

Figure 2 shows side views of two current designs. In Fig. 2a there are projections at the rear for streamlining, and the outer surface of the shell has ridges, while in Fig. 2b the shell is smoother, and there is no rear projection. The trend has been to produce ‘one-size-fits-all’ helmets, rather than manufacturing two or more liner sizes, by using an adjustable circumference plastic harness, similar to that in industrial helmets. Some current, and all earlier, helmets were supplied with soft foam comfort pads of a range of thickness, that were attached by Velcro at several sites inside the liner.

Although oblique impact tests are used for motorcycle helmets (BS 6658, 1985), these are not required for bicycle helmets. The objective is to test current helmets in oblique impact, measuring the linear and rotational acceleration of the headform.

Fig. 1  Plan view of vents in: a) 1994 Troxel ‘Apex’, b) 2002 Giro ‘Targa’ helmets. Helmet front at top.

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ANALYSIS OF BICYCLE HELMET IMPACTS

Analysis allows the detailed interpretation of impact data, and it may confirm the type of responses seen. There are two main approaches to modelling of bicycle helmet impacts:

Lumped parameter models

Hui and Yu (2002) used a lumped parameter model, in which masses, springs and viscous dampers interact. Their model, largely an adaptation of Gilchrist and Mills (1994) model for motorcycle helmets, only works for an impact normal to the helmet surface. Some input parameters, such as the shell stiffness, can be measured experimentally; others, such as damper constants, are disposable constants. Such models cannot predict the helmet impact response from the material properties and the helmet geometry alone. Compared with the 4 mm thick shells of motorcycle helmets, the 0.3 mm thick microshells of bicycle helmets have negligible mass and negligible load spreading ability. Hui and Yu’s model predicts high frequency oscillations in the striker force, which are not present in their experimental impact acceleration vs. time traces; for the crown of a bicycle helmet with large vents impacting a flat anvil with 25 or 50 J energy, these show two main peaks. As they do not analyse the trace to produce a striker force vs. helmet deflection graph, it is impossible to compare their helmet response with those of Mills (1990).

Finite Element Analysis (FEA)

FEA was carried out for polystyrene foam helmet liners, using the materials data of Masso-Moreu and Mills (2003) for extruded polystyrene foam of nominal density 35 kg m$^{-3}$ (XPS35). In ABAQUS 6.2, the foam is considered as being elastic at small strains, and being a Crushable Foam at
larger strains. In the *Elastic* model, the parameters Young’s modulus \(E = 10\) MPa, and Poisson’s ratio \(\nu = 0.1\) match the uniaxial tensile elastic response of the foam.

The *Crushable Foam* model is for isotropic materials, which harden as the volume changes. The equation of the yield surface, which describes the stress states that cause yielding, is

\[
\left( p - \frac{1}{2} (p_e - p_t) \right)^2 + \left( \frac{a\sigma_e}{b} \right)^2 = a^2
\]

where \(\sigma_e\) is the von Mises equivalent stress, and \(p\) is the hydrostatic pressure component of the stress tensor. The section of the yield surface in the \(p\) \(\sigma_e\) plane is an ellipse, with half axes \(a\) and \(b\) in the \(p\) and \(\sigma_e\) directions respectively. The ellipse intercepts the \(p\) axis at \(-p_t\) and \(pc_0\), respectively the initial yield pressures in hydrostatic tension and compression. When the foam hardens, the ellipse increases in size, with the same axial ratio, with the coordinate \(p_t\) at the left remaining fixed, while that at the right moves to \(p_C\). The uniaxial compressive response on loading can be fitted with

\[
\sigma = \sigma_0 + \frac{p_0 \varepsilon}{1 - \varepsilon - R}
\]

where \(\sigma\) is the compressive stress, \(\varepsilon\) the strain, and \(R\) the foam relative density. For XPS35 the initial yield stress in compression \(\sigma_{C0} = 290\) kPa and effective cell gas pressure in the undeformed foam \(p_0 = 150\) kPa.

In the *Crushable Foam* model, the parameters were:
1) \(pc_0\) measured at impact strain rates as 0.15 MPa.
2) It is virtually impossible to measure \(p_t\). The uniaxial tensile yield stress of the XPS35 foam, at strain rate of \(1.6 \times 10^{-2}\) s\(^{-1}\), is 0.5 MPa. Although the ABAQUS manual suggests using a low value \(p_t = -0.05 pc_0\), a value of \(p_t = 0.15\) MPa was chosen for stable modelling.
3) Tabulated data for \(\sigma_e\) versus the true compressive inelastic strain \(\varepsilon_T\). The first row of this table is the initial yield stress \(\sigma_{C0}\) at zero true strain.

The compressive true strain is defined by

\[
\varepsilon_T = -\ln \lambda
\]

where \(\lambda\) is the extension ratio in the compression direction. For uniaxial compression, the Poisson’s ratio in the post-yield regime is zero. Consequently \(\varepsilon_T\) is also equal to the true volume strain. No allowance is made for the elastic strain, so \(\varepsilon_T\) = \(\varepsilon_T\). The program calculates the horizontal diameter of the yield surface as a function of the true volume strain.

Although typical bicycle helmets contain EPS of density > 35 kg m\(^{-3}\), these foams had not been characterised in rapid hydrostatic compression. Consequently, FEA was performed for XPS35; it is assumed for denser foams that the predicted forces will be a multiple of the values for XPS35.

**FEA predictions**

The cycle helmet foam liner was assumed to have no ventilation slots, and to have a uniform 30 mm thickness. The rigid headform had radius of curvature 120 mm in the fore and aft direction, and 80 mm in the side-to-side direction. The fit of the headform to the liner interior is not critical. However for motorcycle helmets, load spreading by the thick shell is only effective if the headform is a good fit to the liner shape (Mills, unpublished).

The impact site was off-centre on the coronal plane (the vertical plane containing both ears). Impacts were with a flat rigid plane, the kerbstone of BSEN 1078, or a rigid hemisphere of 50 mm radius. Figure 3 compares the loading curves for the three anvils. The impact sites are 30° from the crown for the kerbstone and flat anvils, but 60° for the hemisphere (close to the helmet lower edge). The responses are nearly linear, with loading slopes 337, 150 and 81 N mm\(^{-1}\) for the flat, kerbstone and hemispherical anvils respectively.
A linear relationship is predicted by Mills’ (1990) simplified analysis for impacts on a flat surface, assuming no load spreading, and a foam with a constant yield stress $\sigma_y$; the force $F$ transmitted by the foam is

$$F = A\sigma_y = 2\pi R\sigma_y x$$

(4)

where $R$ is the radius of curvature of the head and $A$ the contact area between the foam and the road surface. Equation (4) predicts a slope of 326 N mm$^{-1}$ for a mean helmet outer radius of 130 mm and an initial yield stress of 0.4 MPa; it underestimates the FEA loading slope for a flat surface impact by 3%.

Figure 3 shows the predicted stress fields for impacts on flat and kerbstone anvils. In Fig. 4a the compressive stress contours in the foam are nearly parallel to the applied load direction. The stress is nearly constant in the contact area, but decreases rapidly outside it, confirming the approximation behind equation (4). For the kerbstone impact (Fig. 4b), the foam stress is non-uniform in the contact area, increasing towards the centre. Analysis showed that a 0.5 mm thick shell, made from a thermoplastic of Young’s modulus 2 GPa, raised the loading slope by 11%. Other factors, such as the non-ideal fit of the headform to the inner surface of the helmet liner, reduce the loading slope. Therefore the analysis of equation (4) is reasonable for flat anvils, but inappropriate for other shapes.

EXPERIMENTAL IMPACTS

In the test rig, described by Halldin et al (2001), the vertical velocity component can be up to 5 m/s and the tangential component up to 5 m/s. A free falling headform impacts a horizontally moving
steel plate, moved by a pneumatic cylinder of 1 m stroke. A standard horizontal velocity of 5.0 m/s was used. A rough road surface was simulated by grade 80 SiC grit grinding paper, bonded to the steel plate, the lower surface of which slides on a PTFE layer. The hollow aluminium headform of mass 4.7 kg, with a PVC plastisol skin (Ogle Ltd), has at its centre of gravity a Kistler 8792 triaxial linear accelerometer and a Kistler 8838 rotational acceleration transducer, with its axis aligned with the helmet rotation axis. The headform was modified by attaching a 4 mm thick layer of Astrosorb M3 soft rubber (www.astron2000.au) then an acrylic wig. Gambarotta et al (2002) analysed scalp mechanical properties but did not give elastic moduli. Consequently it is not possible to ensure an exact match in modulus. X-ray CT scans of heads show a variable scalp thickness, so the 4 mm value is an average. The helmet chin straps are fastened under a wooden chin; it would be more realistic to have some compliant material under the chin.

The acceleration traces are recorded at 10 kHz without filtering. However the rotational acceleration signal can be noisy during and after the peak of the linear acceleration. As it is unlikely that rotational acceleration peaks lasting < 1 ms are injurious, the rotational acceleration signal was filtered by a moving 5 point average.

The effect of scalp soft tissue

The modified Ogle headform was dropped from 10 cm onto a flat rigid anvil. The vertical headform acceleration was integrated twice to give the headform deflection. Fig 5 shows this plotted against the impact force. The computed contact stiffness of 2.8 kN/mm for the higher part of the ‘scalp’ curve compares with Allsop et al’s 6.9 N/mm (1991) for an impact on the temporal-parietal region of a shaved cadaver head, with forces up to 15 kN. Consequently the contact compliance of the test headform is greater than that of Allsop’s cadaver.

![Fig. 5 Force vs. deflection of Ogle headform, for added 4 mm ‘scalp’, and for scalp plus wig.](image)

For a helmet mounted on the modified headform, dropped vertically on to a flat surface, the force vs. deflection graph (Fig. 6) does not support Burdett’s assertion that there is a minimum force before the helmet deforms. Rather it confirms Mills (1990) findings of a near-linear increase in the impact force with the crush distance. The FEA in the previous section predicted a near-linear response with slope 337 N mm⁻¹ for a helmet with no holes, made from EPS of density 35 kg m⁻³. This compares with the experimental slope of 253 N mm⁻¹ for helmet with large ventilation holes made from higher density EPS. The higher yield stress foam has been chosen to compensate for the lower cross section of foam in the contact area. The effect of the 4 mm thick soft rubber layer and the wig on the headform is minor.
Localised headform pressure due to crushing high-density PS foam

There are no reported cases of scalp bruising from the use of cycle helmets, or of skull fractures due to the localised loading. Aldman (1984) stated that a depressed skull fracture was likely in the temporal area if a pressure of > 4 MPa acted on an area < 5 cm². As the parts of the skull covered by helmets are stronger than the temporal region, depressed skull fractures are not expected for pressures < 5 MPa. Crisco et al. (1996) impacted the leg muscle of rats with a 6.4 mm diameter nylon hemisphere to cause contusions; the average pressure over the projected area of the hemisphere reached 9 MPa. Beiner and Jokl (2001) could not decide whether the muscle contusion criterion should involve force, pressure or another mechanical variable. If the criterion for scalp bruising involves the peak pressure, this is only likely for pressures exceeding 5 MPa.

The uniaxial compressive stress strain curve for EPS foam, of density 83 kg m⁻³ from a Bell helmet, is shown in Fig. 7. The initial yield stress is 1.0 MPa. The EPS is denser in helmets with large vents, such as the Giro Targa where the density is 120 kg m⁻³. The section of helmet between two ventilation slots has near-vertical sides, and the width tapers to both the inner and outer surfaces. FEA of the stress distribution across the top of a foam block, with an initial 18° taper angle, subjected to a mean compressive strain of 80% (Masso-Moreu & Mills, 2003) predicts a peak compressive stress of 1.0 MPa, compared with the 0.29 MPa initial yield stress. Consequently, for the helmet section at 80% mean strain, the peak compressive stress in the EPS of density 83 kg m⁻³ is predicted to be 3.3 MPa. This should not cause bruising, and since the foam contacts a large area of the head, it should not cause a skull fracture. The polyurethane (PU) foam, from a ‘Trax’ helmet (Fig. 2b) with a smaller fractional area of ventilation slots, has a lower initial yield stress, so will produce lower pressures on the head.

Fig. 6 Force vs. deflection for Giro Targa helmet, right frontal site, impact velocity 5.4 m s⁻¹ on flat surface.

Fig. 7 Impact compression stress strain graphs for EPS of density 83 kg m⁻³ and PU foam of density 91 kg m⁻³, from bicycle helmets manufactured in 2002.
The effect of helmet ridges, or rear extensions, on rotational acceleration

Several helmets were impacted obliquely at sites where there are ridges or on rear extensions, while other helmets, with smooth outer surfaces and a uniform liner thickness, were tested for comparison. If a cyclist falls forwards, face down, with body parallel to the road, a likely helmet impact site is at the front, with the ‘frictional’ interaction moving the front of the helmet downwards. For impacts on the sides of the helmet, the most likely direction of an oblique impact is to move the impact site rearwards. For an impact site at the rear, it is most likely that the cyclist has performed a somersault, so is moving feet first; the oblique impact will move the rear of the helmet upwards. Fig. 8 gives the experimental data for one helmet, and table 1 the peak values for the tests.

![Graphs](image-url)

Fig. 8 Oblique impact on left side of Targa helmet, with 1.0 m drop: a) resultant linear acceleration, b) rotational acceleration vs. time, c) rotational velocity vs. time obtained by integrating fig b).
Table 1 Peak linear and rotational accelerations, for horizontal velocity 5.0 m s\(^{-1}\)

<table>
<thead>
<tr>
<th>Helmet</th>
<th>vertical velocity m s(^{-1})</th>
<th>Feature at site</th>
<th>Sliding direction</th>
<th>peak linear accel. g</th>
<th>peak angular accel. krad s(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giro ‘Targa’</td>
<td>4.43</td>
<td>Front Peak</td>
<td>Down</td>
<td>127</td>
<td>4</td>
</tr>
<tr>
<td>Giro ‘Targa’</td>
<td>4.43</td>
<td>Left Large vents</td>
<td>Rearwards</td>
<td>121</td>
<td>8</td>
</tr>
<tr>
<td>Giro ‘Targa’</td>
<td>5.42</td>
<td>Right Large vents</td>
<td>Rearwards</td>
<td>141</td>
<td>7</td>
</tr>
<tr>
<td>Giro ‘Targa’</td>
<td>5.42</td>
<td>Rear projection</td>
<td>Down</td>
<td>68</td>
<td>2</td>
</tr>
<tr>
<td>Met ‘Maxtrak’</td>
<td>5.42</td>
<td>Crown ridges</td>
<td>Rearwards</td>
<td>157</td>
<td>5</td>
</tr>
<tr>
<td>Met ‘Sfero’</td>
<td>5.42</td>
<td>Front Large vents</td>
<td>Down</td>
<td>133</td>
<td>4</td>
</tr>
<tr>
<td>Knucklebar ‘jumper’</td>
<td>5.42</td>
<td>Front Thick shell</td>
<td>Rearwards</td>
<td>170</td>
<td>4</td>
</tr>
</tbody>
</table>

The peak linear acceleration was noticeably lower (Table 1), when a Giro ‘Targa’ helmet was hit on a rear projection where the foam was 60 mm thick, than for other sites where the liner was of uniform thickness of 25 to 30 mm. The peak rotational acceleration is lower, in spite of the impact point being further from the headform centre. The rotational acceleration traces often had a positive and negative excursion at the time of the peak linear acceleration; this may be an artefact of the accelerometer, so was ignored in assessing the peak values. The peak has little effect on the rotation velocity (Fig. 8c). As the axis of the rotational accelerometer was not perfectly aligned with the axis of rotation, it is likely that the rotational signals are slight underestimates.

In many of the helmets, the liner fractures at several points, but the microshell remained intact, keeping the helmet on the headform. The sliding distance is lower than 5 mm, judging from the length of the sliding indentations on the helmet microshell. Hence there are high frictional forces at the interface between the helmet and the rough surface. Later, the shell begins to roll on the rough surface. Rotation of the helmet on the headform is easier about an ear-to-ear axis (Fig. 9a) but almost impossible about a neck to crown axis (Fig. 9b).

The maximum linear headform acceleration is hardly affected by the tangential velocity component; a Targa helmet dropped on right frontal site at 5.4 m/s had a 132 g peak acceleration, compared with 141 g when a tangential velocity component was added at a similar site.

Fig. 9 Met ‘Sfero’ helmet rotated rearwards, when obliquely impacted on the front. No vertical rotation, but small lateral rotation, when Giro Targa helmet impacted rearwards on the left.

**Helmet coverage of the headform**

Fig. 10 compares lateral views of a helmet from 1994 with one from 2002, on an Ogle headform. The coverage of the 2002 helmet ends further up the headform, and more of the vulnerable
area above the ear is exposed. It is not clear whether test houses check the coverage required by EN 1078 using the smallest or the largest claimed head size.

Peoplesize software (Open Ergonomics Ltd, Loughborough, Leics. UK) shows that the distance from the tragion (ear opening) to the crown of the head varies from 110 mm (5th percentile female adult) to 143 mm (95th percentile male adult). Since helmets appear to avoid covering the ear of the 5th percentile female, it is likely that a 95th %ile male could have a 30 mm gap between the top of his ear and the lower edge of the helmet. More surveys of helmet coverage are necessary.

Fig. 10. Coverage of head from a) 2002 MET ‘Maxtrack 2’, and b) 1994 Troxel ‘Apex’ helmet

DISCUSSION

Kerbstone or flat anvil

FEA predicts that the force vs. deflection response onto a kerbstone anvil has approximately 50% of the slope of that for an impact onto a flat anvil. In standards there is a higher impact velocity onto a flat surface than onto a kerbstone, since the former is more frequently impacted. In our view the flat surface impact is more important. A helmet foam, of optimum density and thickness for an impact with a flat surface at a given velocity, has a too low yield stress for an impact on a kerbstone at the same velocity, or for an impact on a flat surface with a higher velocity. Hence it is not possible to have an optimum design for all impacts.

Role of scalp tissue

Results show that scalp tissue is likely to play a small part in the force vs. helmet deflection response for impacts normal to the helmet surface. Although helmet liner densities have been increased to compensate for the presence of large ventilation slots, this does not lead to pressures on the skull that will cause bruising or injury. Such vents are necessary for efficient head cooling, needed to make helmets acceptable.

Optimum headform for testing

The test headform, with a soft rubber scalp and wig, used in a bicycle helmet with the comfort padding and interior headband, allows realistic helmet rotation in oblique impacts, so it is likely to affect the headform rotational acceleration in an oblique impact. In contrast Halldin et al (2001) used a bare Ogle headform in a motorcycle helmet with no comfort foam, the liner of which was an exact fit to the headform; as no rotation occurred at the headform/helmet liner interface, the benefits of a shearing layer in the helmet may have been exaggerated. The level of rotational acceleration was rarely greater than 5 krad s\(^{-2}\), so it is unlikely that any diffuse brain injury would occur, if the criteria of Gennarelli and Thibault (1989) are valid (rotational accelerations > 10 krad s\(^{-2}\) and rotational velocities > 100 rad s\(^{-1}\)).
Injury severity as a function of impact energy

Results show that the impact force rises nearly linearly with the crushing of the helmet foam, as for 1990’s helmets. This is confirmed by FEA and refutes Burdett’s (2002) claim that serious injuries can occur in minor crashes due to the impact force being just sub-lethal. The peak linear acceleration in an oblique impact test does not appear to be significantly changed from the value measured in a BSEN 1078 test, for the same velocity component perpendicular to the anvil. Consequently the EN standard leads to helmets which keep the head linear acceleration at reasonable levels, so long as the impact site is one of those tested. Ideally, the foam should bottom out, at approximately 90% compressive strain, when the total impact energy of the test has been dissipated. The peak force should not exceed the 10 kN, which causes a head acceleration of about 200 g.

Protection for high speed impacts

Comments about helmets being ineffective if the impact velocity exceeds 20 km/h are misleading; ‘velocity’ should read ‘velocity component, perpendicular to a rigid object’. Helmets are likely to be effective unless the cyclist’s head strikes a moving vehicle at an excessive relative velocity, or has an oblique impact into street furniture with an excessive velocity component.

Limiting head rotational acceleration

It is not possible to perform oblique impacts of an unhelmeted headform, with a 1.5 m drop, because the instrumentation would be damaged. Consequently it is not easy to prove that wearing a helmet reduces the rotational head acceleration. However, without a helmet, it is highly likely that the bicyclist would suffer a skull fracture and severe brain damage.

Area of head coverage

The area of head coverage is limited, especially for those with long (chin to crown) heads. This can leave the temples, and the region above the ears, dangerously exposed. Impacts should be performed low at the sides of helmets, since this is a common impact site in crashes. However the headform used would rotate so that the metal jaw impacted the flat anvil, giving unrealistically high linear acceleration values; some reconsideration of the test headform is necessary. Depreitere et al (2003) also say that head coverage should be reconsidered; they found that 57% of impacts occurred at the side and 27% at the front of the head, and that the lower parts of these areas that are not covered by current bicycle helmets.

Changes to standards

It is impossible to predict, from the perpendicular impacts in BSEN 1078, the performance of bicycle helmets in oblique impacts. The experiments reported here show a range of rotational acceleration levels, due to differences in helmet design. There should be an oblique impact test in EN1078, to encourage the development of designs which minimise head rotational acceleration.

Consumer advice on helmet choice

We are not able to advise consumers that a particular helmet has a superior protective performance. Purchasers should check the fit of the helmet to their particular head shape, and that there is reasonable coverage of the temples. They should wear the helmet with the brow as low as possible, consistent with not restricting vision.

CONCLUSIONS

Most criticisms of current bicycle helmet designs are not valid: the lack of a scalp on test headforms does not lead to inappropriate designs; the foams used in helmets with large vent areas do not cause excessive pressure on the head; there is a gradual rise in peak impact force with impact kinetic energy, not a just sub-lethal level for minor impacts.

Current designs provide adequate protection for oblique impacts on to a road surface, in terms of the peak linear and rotational head accelerations. Helmet designs, with long extensions at the front and rear, do not appear to cause excessive rotational head acceleration. However the coverage at the side of the head is felt to be inadequate.

It is recommended that an oblique impact test, using a headform with realistic scalp and wig, is included in EN 1078 with measurements of rotational acceleration.
Acknowledgment
The authors thank EPSRC for support under grant R89790.

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