Critical evaluation of the SHARP motorcycle helmet rating

N.J. Mills

Metallurgy and Materials, University of Birmingham, UK
Phone 0121 414 5185, email n.j.mills@bham.ac.uk

Abstract

The Department for Transport introduced a safety helmet assessment and rating program (SHARP) for motorcycle helmets sold in the UK. The mechanics behind the part of the scheme that uses a rigid-sphere head-plus-helmet model to estimate the peak headform acceleration in oblique helmet impact tests, is assessed and the approximations exposed. Finite Element Analysis, of a deformable helmet with a realistic shape, is used for comparison. The statistical analysis of motorcyclists' impact velocities, sites and impact type, used to weight the SHARP impact results, is also reviewed. Conclusions are reached on the meaning of the derived oblique impact test results, and validity of the star rating.

Keywords: helmet, standards, motorcycle, modelling

1 Introduction

According to UK Regulations, motorcyclists must wear a helmet that is certified to either BS 6658 (1985) or ECE Regulation 22/05 (1999), standards that set minimum performance requirements in a number of areas. Mellor et al. (2007) summarized Department for Transport (DfT) research into improved helmet standards, and suggested methods for a star rating, given the acryonym MHAP. In 2008 the DfT introduced a safety helmet assessment and rating program (SHARP) that was similar to Mellor et al.'s scheme, which aimed to inform motorcyclists of the differences in helmet performance, so that they could make informed choices when purchasing helmets. The one- to five-star ratings did not necessarily correlate with the price of helmets, which caused some surprise. One- to five-stars are used in European NCAP ratings for new cars; the well-established test methods are defined at www.euroncap.com. However the website http://sharp.direct.gov.uk does not reveal full details of SHARP tests or the protocol for treating results to obtain star ratings; these are described by Halewood and Hynd (2008) in a report that is not publicly available. As oblique impact tests on motorcycle helmets have recently been analysed (Mills et al. 2009) using Finite Element Analysis (FEA), it is possible to assess the part of the SHARP protocol that considers oblique impacts.

2 Oblique impacts of tennis balls and other helmet types

It is useful to review the phenomena in other types of oblique impact, and the modelling required to reproduce those phenomena.

When a tennis ball makes an oblique impact with a court, the initial sliding is usually followed by rolling. Roetert and Groppel (2001) stated that the ball slides throughout the entire length of the impact with the court if the impact angle is sufficiently shallow, or the incoming ball velocity is sufficiently fast. FEA of tennis ball oblique impacts (Goodwill et al. 2005) showed that the ratio of friction force to reaction force was constant during the initial sliding, but then fell rapidly, becoming negative at the end of the contact. The time variation of the force normal to the rigid

court was almost independent of the tangential velocity (0 or 25 ms^{-1}), when the normal velocity was kept constant at 15 ms^{-1}.

Mills and Gilchrist (2008a) performed oblique impacts on various sites on bicycle helmets using a headform containing linear and rotational accelerometers. The peak rotational acceleration was strongly dependent on the impact site and direction, and typical values were thought to be insufficient to cause diffuse axonal injury in the brain. FEA of the impacts (Mills and Gilchrist 2008b) showed that the friction coefficient, at the interface between the helmet interior and the headform with a wig and scalp, was typically 0.2 in the experimental tests.

Oblique impact tests on American football helmets (Finan et al. 2008) showed that a reduction in the friction coefficient of the helmet exterior led to reductions of peak head rotational accelerations on some sites and increases on others. This could not be explained using a rigid sphere model for the helmet.

The angular inertia of a typical motorcycle helmet is much greater than that of a tennis ball, but the principles applying to the oblique impacts are the same. Therefore sliding and rolling may be expected in motorcycle helmet oblique impacts, and FEA is needed to simulate the events in the highly deforming system.

3 SHARP impact tests: measurements and derived parameters

The SHARP website describes direct impact tests using a rig in which two guide wires restrain the headform from rotation, during its fall under gravity, and during the impact (as in BS 6658 tests). Five impact sites were used (front, left, right, crown and rear, see figure 1), with velocities *V* equal 6.0, 7.5 and 8.5 ms^{-1} onto both flat and kerbstone anvils. Halewood and Hynd (2008) described a total of 5 x 3 x 2 = 30 impacts for each helmet model assessed. Three sizes of helmet were allocated to these tests, using headforms of the appropriate size (size J has 57 cm circumference and mass 4.7 kg, size L has 60 cm and 5.6 kg, size O has 62 cm and 6.1 kg).
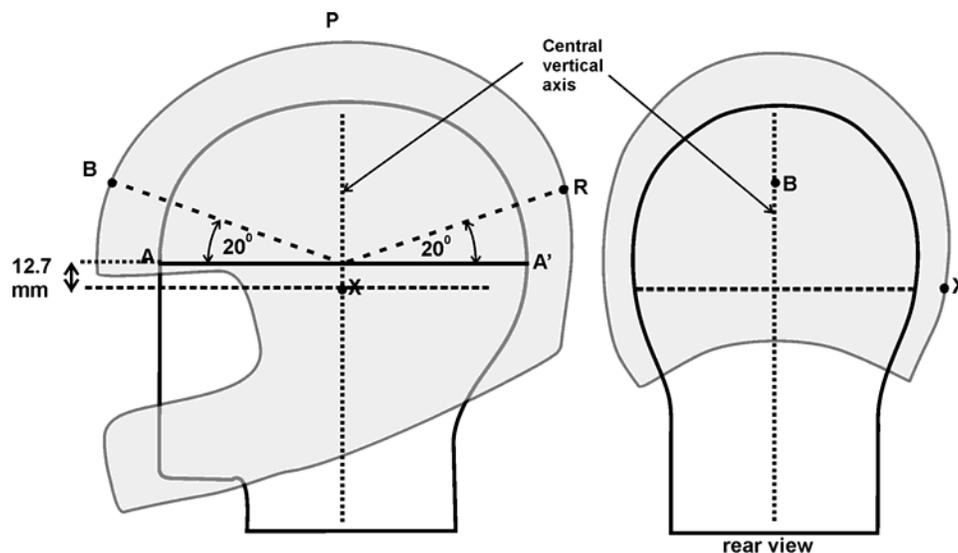
Fig. 1. Impact sites in Regulation 22/05: X side, B front, R rear, P crown.

The SHARP website justifies the use of a guided headform rig, instead of a free headform rig as in Regulation 22/05, stating that Mellor et al. (2007) found that the former results were more repeatable (the peak headform linear accelerations had standard deviations of 0.9% and 2.3%

respectively). Thus the SHARP test rig uses the variable headform mass of Regulation 22/05 with the guidance system of BS 6658. Thom, Hurt and Smith (1998) found that peak linear accelerations were about 10% lower when headform rotation was allowed, presumably because the headform centre of gravity could achieve a lower minimum position. In real life, the neck provides very little resistance to rotation on the 10 ms time scale of a helmet impact, so the head can freely rotate; hence it is more realistic to use the Regulation 22/05 rig. Regulation 22/05 allows a peak linear headform acceleration of 275 g, compared with 300 g in BS 6658, which roughly compensates for the headform rotation factor, so a helmet that passes the direct impact test in one standard should pass it in the other.

The SHARP website also describes Regulation 22/05 oblique impacts, with vertical impact velocity $V = 8.5$ ms^{-1} on to an abrasive anvil at $\theta = 15°$ to the vertical (Figure 2). The impact sites were at the left and right, at X in figure 1, with the helmet falling face-downwards. The impact sites used in COST 327 are shown in figure 2, with the helmet falling face-upwards. Glaister et al. (1983), who developed the rig, found that, when V was increased from 5.4 to 12.9 ms^{-1}, the peak forces F_N and F_T increased proportionately. Therefore, the parameters V and θ affect the severity of the impact.
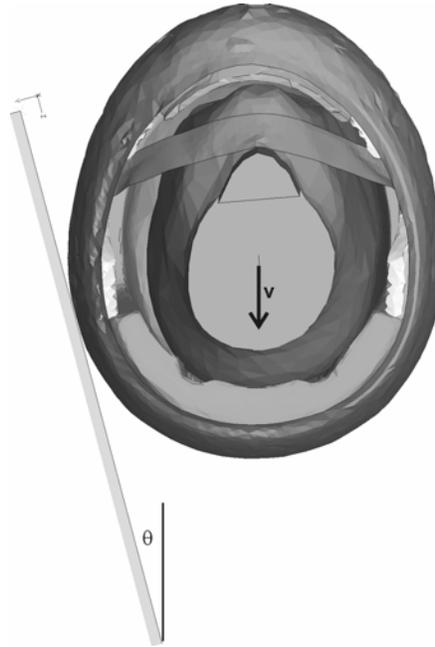
Fig. 2. Typical helmet orientation used in COST 327 oblique impacts; helmet falls vertically with velocity V, hitting a planar abrasive anvil at angle $\tilde{\theta}$

The friction coefficient μ was calculated using

$$\mu = F_T^{\max} / F_N \tag{1}$$

from the peak tangential force $F_T^{\max}$ and the value of F_N at the same time.

The SHARP protocol analyses three groups of 15 results: direct impact tests on a flat anvil, direct impact tests on a kerbstone anvil, and equivalent oblique impacts calculated from the first group. The direct impact tests will not be commented upon further. It is third group of derived 'results' that is of concern; Halewood and Hynd calculated oblique peak acceleration $A_R^{\max}$ with units of g (9.81 kg m s^{-2}) using

$$A_R^{max} = A_N^{max} \sqrt{1 + \mu^2}$$

(2)

where A_N^{max} is the peak headform linear acceleration component in the direction normal to the flat anvil, and μ the friction coefficient. The subscript R indicates a resultant (vector sum) of the acceleration components A_N normal to, and A_T tangential to, the anvil surface. Superscripts *max* have been added to their symbols to indicate maximum values.

They state the *oblique peak acceleration* 'is an estimate of the resultant acceleration that would be endured by a head in an oblique impact'. They claim, as rotational acceleration is directly proportional to tangential force, which is directly proportional to the friction coefficient, 'this new parameter can give a good indication of how the helmet performs rotationally'.

They calculated an equivalent oblique impact velocity V using

$$V = V_N / \sin \theta$$

(3)

The velocity component V_N normal to the anvil equals the value in the direct impact test. They deduced from the COST 327 accident data (discussed in section 9) that the mean oblique impact angle $\bar{\theta}$ = 37.5°, so, from equation (3), V =1.64 V_N. Hence they derived 15 pairs of data (A_R^{max}, V) from direct impact data on flat anvils. Their μ values ranged from 0.54 to 0.86 with a mean of 0.68 (which seems rather high) so the correction factors in equation (2) ranged from 1.136 to 1.319. In the COST 327 report, the μ values for AGV full face helmets with ABS shells were 0.53±0.03 and 0.56±0.04 depending on the liner density, and for similar helmets with GRP shells 0.44±0.03 and 0.47±0.03 depending on the shell construction.

4 SHARP model for head acceleration

4.1 Assumptions of the helmet model
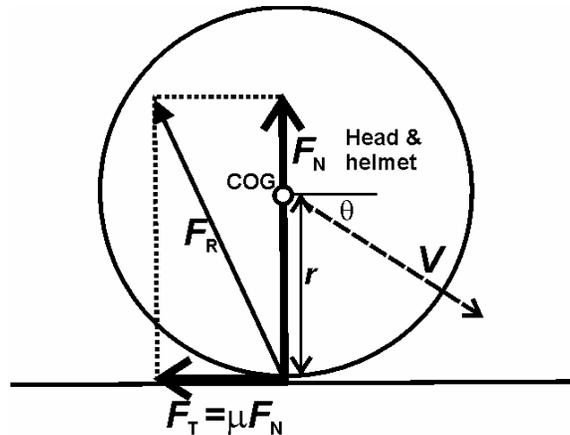
Fig. 3. Spherical rigid helmet plus head model, of the type used by Halewood and Hynd: impact velocity V, impact force components F_N normal and F_T tangential to the road surface.

Equation (2) is based on a simple model of a rigid spherical head/helmet sliding on a flat road surface, used by Halewood and Hynd (Figure 3). They did not mention the approximations used in the model (all turn out to be incorrect):
(1) The helmet slides, rather than rolls, on the road surface for the whole of the impact,

(2) the external geometry of the rigid helmet remains spherical,
(3) hence there is a point contact between the helmet and the road.
(4) The head's centre of gravity is located at the centre of the helmet sphere.
(5) The shape of, and conditions at, the interface between the head and the helmet interior can be ignored, i.e. the head exactly fits the helmet with no slip at the interface.

Point (1) was deduced from oblique impact tests described in chapter 8 of COST 327 (2001); the helmets fitted the headform (metal with a plasticized PVC scalp) well, and the chin strap was tight under the chin. Figure 4 shows the linear relationship between tangential force and normal force during one such test. However extrapolation of this relationship to higher forces is not valid, as will be explained below.
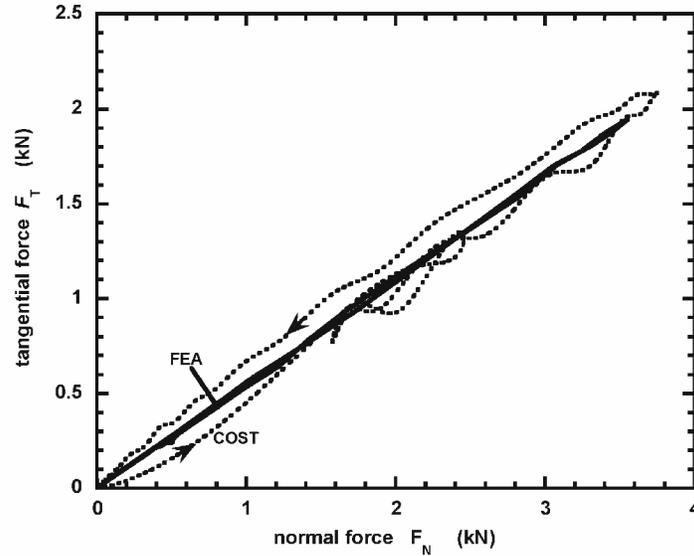
Fig. 4. Correlation between tangential force and normal force in a COST 327 impact at side of AGV helmet (from Mills et al, 2009).

4.1 Sliding or rolling

In figures 3 and 5 the tangential force F_T acts at a distance approximately equal to the helmet radius r from the headform centre of mass. Hence its moment about the headform centre of mass is related to the headform angular acceleration $\ddot{\theta}$ by

$$F_T r = I\ddot{\theta} = mk^2\ddot{\theta} \qquad (4)$$

where I is the angular inertia, m the mass, and k the radius of gyration of the headform plus helmet. The headform angular velocity $\dot{\theta}$, zero before the impact, is given by integrating equation (4) with respect to time t

$$I\dot{\theta} = \int_0^t F_T r \, dt \qquad (5)$$

Equation (5) relates the angular momentum of the headform and helmet to the angular impulse provided by F_T. If the helmet velocity V_T tangential to the road remains almost constant, rolling will commence when
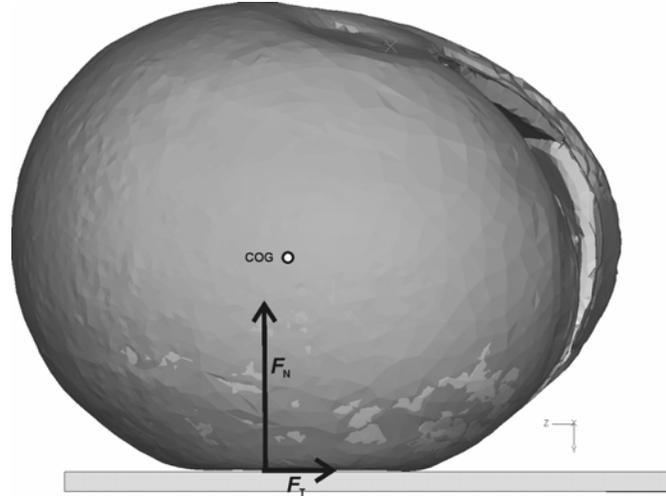
Fig. 5. Contact area between a Mavet helmet and a flat road surface at the peak of an impact (FEA simulation with $V_N = 7.5$, $V_T = 9.8$ m/s of Table 1, after 5.1 ms).

$$\dot{\theta} \, r = V_T \tag{6}$$

Mills et al. (2009) substituted equation (6) in equation (5) and assumed that r is constant, to calculate the tangential impulse J_T, defined by

$$J_T \equiv \int F_T \, dt \tag{7}$$

This reached a maximum value when rolling starts, given by

$$J_T^{max} \cong \frac{I V_T}{r^2} \tag{8}$$

Hence, a limited tangential impulse J_T^{max} is required to make the helmet and headform roll on the anvil in an oblique impact.

If the normal component V_N of the oblique impact velocity is increased, the peak normal force increases almost in proportion (see Figure 8 later). Therefore, if V_N is increased while V_T is kept constant, the tangential impulse limit will be reached before the end of the impact, and rolling will commence during the impact. If this happens before the normal force reaches its peak value, the peak tangential force will be smaller than the value computed using equation (1).

4.2 F_N and F_T contributions to the headform rotational acceleration

Assumptions (3) and (4) mean that the reaction force normal to the anvil acts through the headform centre of gravity (Figure 3), so it does not cause any rotational acceleration. However, helmet external surfaces are initially non-spherical, and they deforms so their contact area with the road is large at the peak of the impact (Figure 5). The normal forces, distributed over this contact area, can be summed to give a total force F_N, acting at a point. The line of action of F_N usually does not pass through the headform centre of gravity, so F_N contributes to the headform rotational acceleration; typical values are calculated in section 8.

Halewood and Hynd discussed figure 8.4 of the COST 327 report, which shows a linear relationship between peak tangential force (N) and peak headform rotational acceleration (rad s^{-2})

$$\left|\ddot{\theta}\right|^{max} = 3.17\,F_T^{max} - 153$$

(9)

The correlation coefficient was $r = 0.97$, for oblique impacts at the sides of four types of AGV helmet, with angle $\theta = 15°$ and impact velocities $6 < V < 12$ ms^{-1} ($1.5 < V_N < 3$ ms^{-1}). Any relationship, established for a limited range of a variable, should not be extrapolated outside that range. Section 6 shows that equation (9) breaks down when either higher V_N values or other impact sites are considered. The V_N values in the SHARP derived results were between 2.7 times and 3.9 times those used to determine the friction coefficient.

4.3 Oblique peak acceleration

Halewood and Hynd's method of 'assessing helmet performance with regard to rotational acceleration' started with the resultant force F_R on the helmet during an oblique impact, given in terms of the normal and tangential forces by

$$F_R \equiv \sqrt{F_N^2 + F_T^2} = F_N\sqrt{1 + \mu^2}$$

(10)

The right hand end of this equation is only valid if the tangential force is $\mu\,F_N$; it ceases to be valid if the helmet rolls on the road surface. They deduced from equation (10), without giving the reasoning, that the oblique peak acceleration A_R^{max} in an oblique impact is given by equation (2). For such a deduction to be valid, the resultant force F_R must be proportional to A_R^{max}. Newton's second law for the acceleration A of a rigid body of mass m

$$F_R = m\,A_R$$

(11)

links the resultant force to the resultant acceleration, and force components to acceleration components. Halewood and Hynd's implied use of equation (11) assumes that the head and helmet can be treated as a rigid body with mass m. However, Mills et al. (2009) showed, in their Figure 11, that equation (11) is a rough approximation for the COST 327 oblique impact data; part of the helmet mass must oscillates in position relative to the headform mass. Substituting equations (11) and (4) into (10) gives

$$F_R = \sqrt{(mA_N)^2 + \left(\frac{m\,k^2\ddot{\theta}}{r}\right)^2}$$

(12)

so, dividing through by m

$$A_R = \sqrt{A_N^2 + \left(\frac{k^2\ddot{\theta}}{r}\right)^2}$$

(13)

Whether a rigid sphere or a deformable helmet model is used, A_R^{max} is the peak resolved linear acceleration of the headform and helmet. Halewood and Hynd stated that A_R^{max} was neither a linear acceleration nor a rotational acceleration; if the rigid sphere model of figure 3 applied to motorcycle helmets, A_R^{max} would equal the specific combination of linear and rotational headform accelerations expressed by equation (13). However, as motorcycle helmets are deformable and non-spherical, neither the model nor equation (13) applies to them.

7

Halewood and Hynd's use of equation (3) implies that the peak headform linear acceleration component $A_N^{\max}$ is the same in an oblique impact, as in a direct impact with the same value of V_N, i.e. it is a function of V_N but not of V_T. This is reasonable; Mills et al. (2009) showed by FEA that $A_N^{\max}$ fell slightly as V_T increased from zero, keeping V_N constant (see also section 7).

Equation (2) for oblique impacts does not contain the angle θ; if θ is reduced from 89° while V_N remains constant, it states the acceleration $A_R^{\max}$ remains constant. However, for the same conditions, equation (3) states that V increases. This contradicts the evidence from the SHARP direct impact tests at different velocities, that $A_R^{\max}$ $(=A_N^{\max})$ increases with V.

5 Linking acceleration parameters to injury mechanisms

Ideally, the headform acceleration parameters measured in helmet tests should directly relate to head injury mechanisms (brain contusions, haematomas, diffuse axonal injury, skull fractures). However, the links are only approximately understood (Zhang et al. 2001). The limits for linear headform acceleration, in motorcycle helmet standards, have been reduced empirically over the years (Glaister 1996).

Chinn et al. (1999) only reconstructed two fatal injuries, both allocated a peak linear acceleration of 350 g, while Mellor (2006) provided a graph of fatality probability versus the peak linear acceleration $A_R^{\max}$ that did not mention injury mechanisms. This graph, consisting of linear segments through the points (0% at 150 g, 7.1% at 200g, 17% at 275 g, 23.5% at 375 g, 100% at 500 g), was used in the SHARP rating. It is based on a small number of cases, with unknown method and accuracy of reconstruction. The 7% probability of fatal injury at 200 g seems high, when analysis of American footballers wearing helmets instrumented with accelerometers (Funk et al. 2007) suggested a 30% probability of mild traumatic brain injury at 200 g.

Recent FEA modelling of brain motion inside the head in an impact (Kleiven, 2007), and dynamic X-ray observations of the motion of markers inside cadaver heads (King et al. 2003), indicated that large brain rotations occur and brain tissue shears during impacts. The severity of diffuse axonal injury (DAI) has been related to the peak head rotational acceleration (Gennarelli 2005). It is strange that DAI is not considered in the SHARP analysis, given that Halewood and Hynd mentioned that peak rotational acceleration correlates with peak tangential force.

Equation (13) implies that a particular combination of linear and rotational acceleration determines the severity of head injuries. Although other combinations of such accelerations have been proposed as head injury criteria (Newman 1986), they have rarely been used.

6 Factors that determine the peak headform rotational acceleration

Equation (9) describes how peak headform rotational acceleration is linearly related to the peak tangential force, for oblique impact tests on a single site with $V_N \leq 2.5$ ms[-1]. Mills et al. (2009) reproduced data from some of the same COST 327 oblique impact tests using FEA. Their validated model predicted that, in more severe oblique impacts with $V_N \geq 5$ ms[-1] at a range of sites, the peak headform rotational acceleration correlated poorly with the peak tangential force (Figure 6). Both the tangential and normal force components contribute to the rotational headform acceleration, as will be shown in section 8.

The peak headform rotational acceleration is affected by the impact site and sliding direction. It is relatively small for impacts on the helmet forehead with the sliding direction downward,
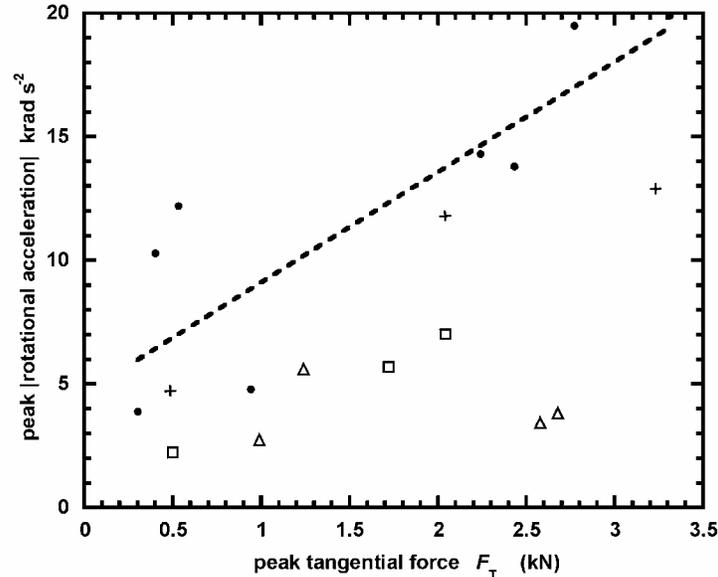
Figure 6. Peak headform rotational acceleration vs. peak tangential force for various impact sites (Mills et al. 2009): dots right site, triangle front, squares crown, crosses half way between crown and right. Dashed line is a best fit to the data.

because the impact force vector, acting well ahead of the headform centre of gravity, counteracts the contribution from the tangential force on the helmet shell. Hence, when considering the wide range of impact velocities, sites and directions, in motorcycle crashes, there is no equivalent of equation (9).

The COST tests used 80-grade alumina paper, which probably has a higher friction coefficient than typical road surfaces. Therefore, in impacts with road surfaces, the rotational head accelerations are likely to be smaller than laboratory tests on alumina paper, with the same impact velocity, site and angle.

7 Factors that determine the peak linear headform acceleration

Aldman et al. (1978) tested motorcycle helmets, comparing linear and oblique impact tests with the same V_N values, and found the peak linear headform accelerations were roughly the same.

Zellmer (1993) performed Regulation 22 direct impact tests on the side of a full-face helmet model, over a range of impact velocities V. His peak linear resultant accelerations A_R^{max} (Figure 7) increased linearly with the velocity component normal to the flat anvil V_N (= V). Graphs (figure 8.3 in the COST 327 (2001) report) showed average oblique impact responses (for $\theta = 15°$, at a side site) for four types of AGV full face helmets. The A_{max} values, taken from these graphs, also increase linearly with V_N, and the data falls close to the trend line for Zellmer's results (Figure 7). If the plot had been against V ($\cong 4V_N$ when $\theta = 15°$) the data would not agree with Zellmer's results. Aare et al. (2004) used FEA to simulate Regulation 22 oblique impacts at the side of a full face helmet, with $\theta = 15°$, $30°$, $45°$ and $90°$, and $V = 3, 5, 7$ and 9 ms^{-1}. Data from their paper, not previously presented graphically, are also shown in figure 7. The agreement between the three sets of data is remarkably good, given that the helmet models differ, and that the experiments used metal headforms while Aare et al. modelled a deformable human head. The results in Table 1, for oblique impacts lower on the side of a Mavet helmet, also have a linear relationship, but the values lie 20% above the trend lines in figure 7.
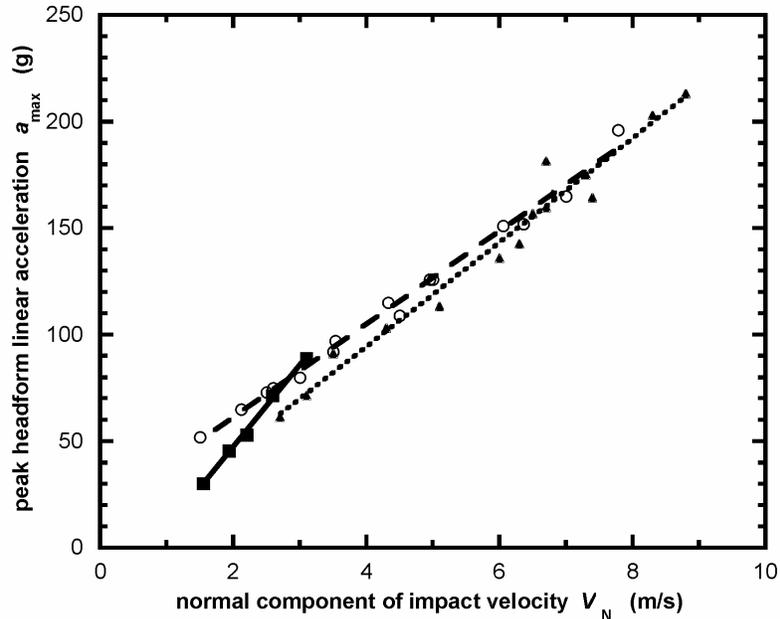
Fig. 7. . Peak resultant linear acceleration vs. normal impact velocity for side impact site: circles direct impacts of Zellmer (1993), squares COST 327 oblique impacts, triangles FEA of Aare et al. (2004). Best-fit straight lines are shown.

The research consensus is that the peak resultant linear acceleration of a headform is a linear function of V_N, but values vary by ±30% depending on the helmet model and impact site. The linear relationship is due to the polystyrene foam liner peak deformation increasing linearly with V_N (Mills, 2007, chapter 16).

8 FEA exploration of a SHARP oblique impact

The FEA model of a Mavet fullface motorcycle helmet, used by Mills et al. (2009), can be used to explore the relationship between direct impact tests, and oblique impact tests at angle θ = 37.5° of the type derived in the SHARP analysis. Oblique impact tests would be preferable, but this would require the construction of new test equipment to achieve the high impact velocities.

The friction coefficient at the helmet road /shell interface μ_R was set at the 0.55 value found for an AGV helmet on abrasive paper in the COST experiments, while that at the head/helmet interface μ_H was 0.2, found for bicycle helmets on a headform with scalp and wig (Mills and Gilchrist 2008b). The headform had mass 4.77 kg, while other details are given by Mills et al. (2009). Table 1 compares predictions for direct and oblique impacts on a right hand site. The peak linear acceleration is slightly smaller in the oblique impact, than in the direct impact at the same V_N. Hence Equation (2) overestimates the peak linear acceleration in a high velocity, oblique impact by about 32% if the friction coefficient μ = 0.55.

The resultant peak rotational accelerations in the direct impacts are less than 10 krad s^{-2}, so are probably non-injurious, but they increase to potentially injurious values for the oblique impacts. The 3-axis component of the rotational acceleration (the tangential velocity V_T is along the 3-axis) is nearly constant, while the 1-axis component (to which F_T contributes) increases significantly in the oblique impact.

Table 1. Oblique impacts, rearwards on the right 80° site, on a abrasive paper surface with $\mu_R = 0.55$, $\mu_H = 0.2$

V_N (ms^{-1})	V_T (ms^{-1})	$|V|$ (ms^{-1})	A_R^{max} FEA (g)	A_R^{max} eq (2) (g)	$\ddot{\theta}_1^{max}$ (krad s^{-2})	$\ddot{\theta}_2^{max}$ (krad s^{-2})	$\ddot{\theta}_3^{max}$ (krad s^{-2})	$|\ddot{\theta}|_{max}$ (krad s^{-2})
6.0	0	6.0	196		5.2	-1.0	5.4	7.2
	7.82	9.84	171	224	14.9	2.8	5.7	15.2
7.5	0	7.93	243		±6.0	-1.5	6.3	8.5
	9.77	12.3	207	277	16.8	3.5	6.7	18.0
8.5	0	8.5	282		6.8	-1.4	6.5	9.0
	11.08	13.9	>227*	322				

*simulation stopped before peak

Figure 8 shows the poor correlation ($r = 0.388$), expressed by

$$|\ddot{\theta}|^{max} = 48.1\, A_R^{max} + 109.1 \tag{14}$$

between the maximum resultant headform rotational acceleration, and the oblique peak acceleration. This confirms that A_R^{max} cannot substitute for the peak rotational acceleration.
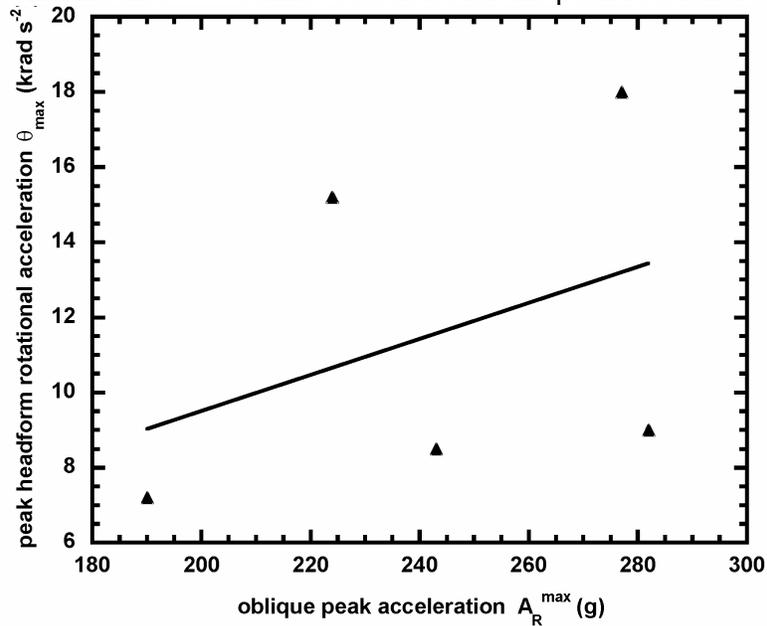
Fig. 8. Peak headform rotational acceleration vs. 'oblique peak acceleration' with best-fit straight line (FEA simulations of Table 1).

Figure 9 shows the contributions of the anvil reaction forces to the moment M_1 acting about the 1 axis of the headform; that from the tangential force F_T is the largest, as expected, but F_N contributes positively for times < 7 ms, then negatively for longer times (its total contribution is almost zero). The sum of the contributions does not equal the headform quantity $I_1\ddot{\theta}_1$ because the headform can rotate in three dimensions, and the helmet can move on the headform. $I_1\ddot{\theta}_1$ does

not rise until 2.5 ms after helmet-to-anvil contact, and its peak value is 30% higher than the peak sum of the moments (although the time integrals of both variables are almost the same). Therefore, in this complex deformable system, equation (4) does not describe the relationship between the contact force F_T and the headform rotational acceleration $\ddot{\theta}_1$.
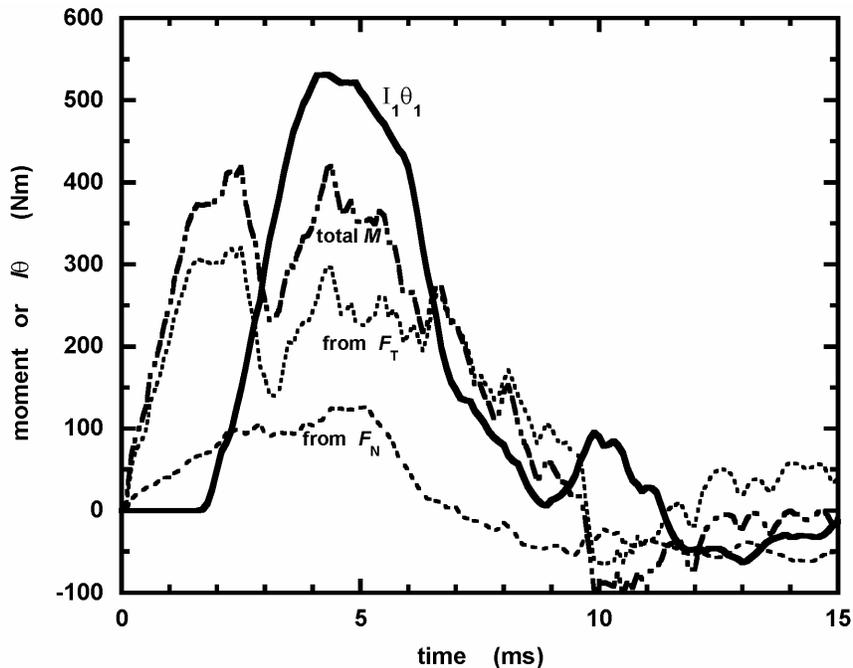
Fig. 9. Contributions of the anvil reaction forces to the moment on the helmet plus headform, compared with the product of headform angular acceleration and angular inertia of headform and helmet, for the 4th simulation in Table 1.

9 Linking the SHARP test results to the risk of fatal injury

The second part of SHARP protocol calculates the annual number of UK motorcyclist fatalities, if all motorcyclists wore a particular helmet model, as the basis of a star rating. It does this by weighting the various test results by the probability that their parameters (site, impact type and velocity) occur in motorcycle accident statistics. Both Mellor et al. (2007) and the SHARP website quote the COST 327 statistics for impact site frequency (27% lateral right, 26% lateral left, 24% frontal, 21% rear and 2% crown). The COST 327 definition of 'lateral left' impact sites (Figure 10) covers all sites to the left of the midplane, with the exception of the crown site 35, hence it is a large part of the helmet. Both Otte (1991), who gave percentages for each of the site divisions shown in figure 10, and Dowdell et al. (1988) showed that the left and right chin bar regions were most frequently impacted, followed by the left and right helmet forehead regions. Halewood and Hynd used the COST 327 statistics as probabilities that five specific Regulation 22 test impact sites (Figure 1) were hit. However, it is a misinterpretation of COST 327 statistics to say that 27% of impacts occur on a specific left site.

   The COST 327 report categorized the shape of the impacted object (79% round, 9% flat, 4% edge (kerbstone), 17% unspecified) and the angle θ of impact (50% < 15°, 17.5% 16°-30°, 8% 31°-45°, 5.5% 46°-60°, 19% > 60°). Halewood and Hynd combined the two categories to deduce that there were 38% flat, 2% kerb and 60% oblique impacts. It is unclear how this was done, and the results cannot be reconciled with the COST statistics: for instance the 79% of round objects struck have been ignored. The percentages were used as probabilities that the test conditions

12

occurred in real crashes: $p_T = 0.38$ for direct impacts on flat objects, $p_T = 0.02$ for direct impacts on kerbs and $p_T = 0.60$ for oblique impacts on flat objects.
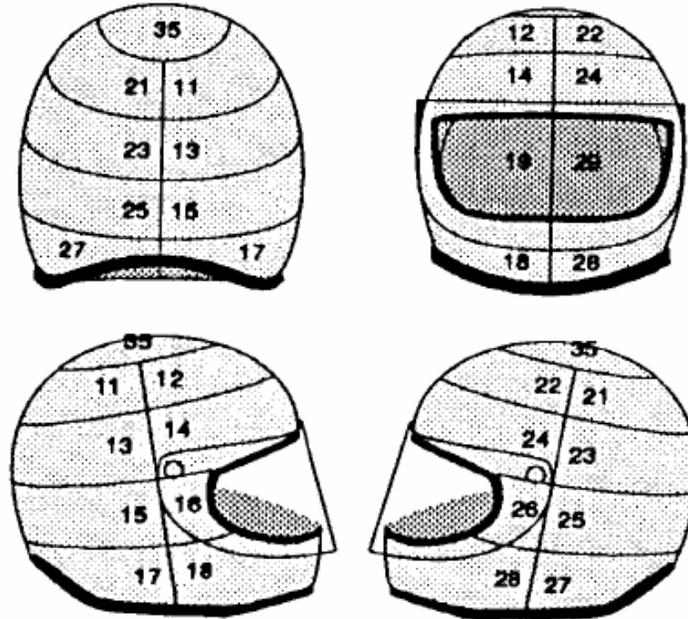
Fig. 10. COST 327 definition of impact sites; lateral left sites are sections 21 to 29.
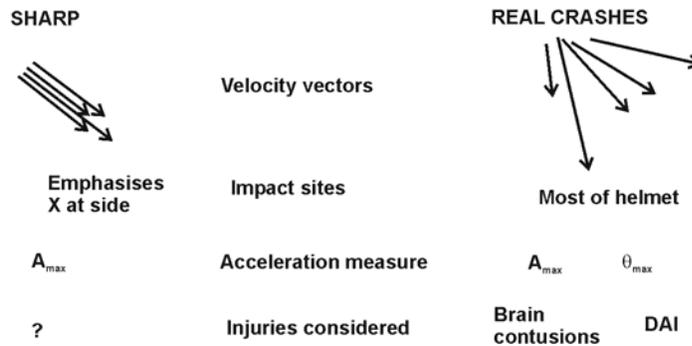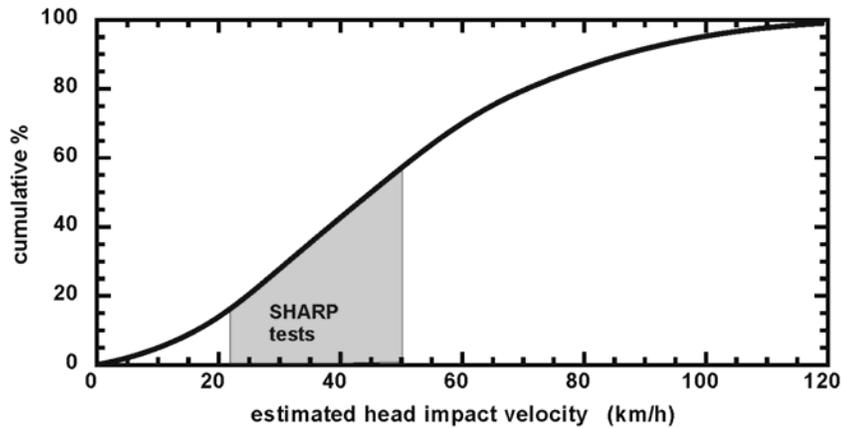
Fig. 2. Schematic for injury calculations, comparing the SHARP scheme with a more realistic one.

13

For each SHARP test result there is an impact velocity, or an equivalent velocity calculated using equation (3); the probability p_V of this velocity occurring in the distribution of crash velocities was calculated. The direct impact results had $8.5 > V > 6.0$ ms^{-1}, while the derived results had $13.9 > V > 9.8$ ms^{-1}. Halewood and Hynd quoted COST 327 data that 32% of crash velocities were between 6 and 14 ms^{-1}. They admitted that their protocol ignored the 68% of impacts with $V < 6.0$ ms^{-1} or $V > 14$ ms^{-1} (Figure 11). p_V was multiplied in turn by the probability p_S that the helmet site, p_T that the impact type occurred, and p_A that the peak linear acceleration caused a fatal head injury (the data mentioned in section 5), to obtain the probability p_F of a fatal injury being sustained. Finally, the p_F were summed over the test results, and multiplied by the annual number ($M = 7087$) of UK motorcyclists whose head injuries were the most serious injury recorded, to give the number of fatalities F

$$F = M \sum p_V p_S p_T p_A \qquad (15)$$

Kerbstone impact test results, with $p_T = 0.02$, have very little effect on the SHARP rating. However, as oblique impacts onto flat surfaces have $p_T = 0.60$, the derived oblique peak acceleration data is heavily weighted. Such derived data have high equivalent velocities, calculated from equation (3), and high $A_R^{\max}$ values, calculated from equation (2); hence they probably contribute the majority of the fatalities estimated using equation (15).

10 Discussion

The SHARP helmet rating scheme has been widely publicised by the DfT in the UK and is mentioned in other countries. However, unlike Euro NCAP, the protocol used to derive the star ratings has not been made publicly available. Given the concerns raised in this paper about the estimation of oblique peak acceleration, and the relevance of these derived results to motorcycle accidents, the protocol should be published and exposed to public debate.

The SHARP scheme estimates the performance of a helmet model over the spectrum of accidents experienced by motorcyclists, rather than in an impact at a single velocity. This, in theory gives more information that the minimum performance levels of Reguation 22 or BS 6658. However, its over-simple model for helmet geometry leads to the erroneous mechanical concept of oblique peak acceleration $A_R^{\max}$. This does not equal the combination of linear and angular head accelerations expressed by equation (13), because the rigid sphere model does not apply to helmet oblique impacts. Further, the extrapolation of oblique impact behaviour, from the $V_N = 2.2$ ms^{-1} impacts of the COST 327 program, to the SHARP oblique 'tests' where V_N can be 8.5 ms^{-1}, is invalid. Even if the combination of accelerations of equation (13) could be directly measured, it would be unlikely to correlate with any particular head injury mechanism. $A_R^{\max}$ merely overestimates the peak linear headform acceleration in some high-impact-angle, high-velocity oblique impacts.

Halewood and Hynd did not consider the limited angular inertia of a typical head plus helmet; when a motorcyclist falls 1.5 m vertically, the tangential impulse, in all but the highest V_T oblique impacts, will be sufficient to cause the helmet to eventually roll on the road during the impact. Furthermore, their model neglected helmet deformation (vital for its protective role), and the likelihood that the layers of scalp, hair and soft comfort foam at the head/helmet interface would slip and/or shear.

Figure 11 compares the SHARP protocol, which assesses impact velocities V in the range 6 to 14 ms^{-1}, with a more comprehensive one. By limiting its analysis to a single impact angle of $\theta =$

37.5°, the SHARP protocol avoids the need to consider whether the impact velocity components (V_N and V_T) causing linear, rotational or a combination of head accelerations. Figure 7 showed that A_R^{max}, for a particular impact site on a helmet model, is determined by V_N. The SHARP protocol, by incorrectly assuming that A_R^{max} is a function of V, overestimates the number of motorcyclists' deaths. Halewood and Hynd's predicted number of fatalities for crashes with velocities between 6 and 14 ms^{-1}, averaged for all the models helmets tested, was four times too great. They provided various explanations for the discrepancy, but not the most obvious one, that V_N should have been used in place of V when estimating the fatalities.

The SHARP ratings are probably more influenced by the highly-weighted but derived oblique peak acceleration data, than by real test results. The site probability p_S for the side site X of Regulation 22/05 is too high; this site is rarely hit in practise, as the rider's shoulder intervenes in falls to the road. Consequently the ratings are unlikely to indicate the real ranking of helmet protective levels. They do not indicate the margin by which helmet models pass the direct impact tests in Regulation 22/05 or BS 6658, whereas www.adac.de provides qualitative data on some German helmets tested to Regulation 22/05 in 2008.

Manufacturers usually design helmets to pass the relevant standard. There is a wide range of tests in these standards (tests at –20 °C and 50 °C, and impacts on the chin bar), and it is impossible to pass flat and kerbstone anvil tests at a specific site by the same margin. Consequently, some tests at an impact velocity of 7.5 ms^{-1} may be passed by a small margin, e.g. with a peak linear acceleration of 260 g when 275 g is the maximum allowed. The graph of peak acceleration vs. impact velocity is approximately linear (Figure 7), but will curve steeply upward when the foam bottoms out. Therefore when a helmet, designed to Regulation 22/05, is impacted at 8.5 ms^{-1} at such a site, the peak linear acceleration will probably exceed 300 g. Such a result could strongly influence the SHARP rating.

A helmet with a high coefficient of friction, when its side obliquely impacts coarse alumina paper, will be penalised in the SHARP calculation algorithm. The coefficient of friction can vary significantly with site, as the material contacted and local curvature or features vary. If manufacturers change helmet designs to increase their SHARP star rating, or the SHARP protocol were incorporated into a future amendment of EC Regulation 22 (as has been proposed), this could encourage the development of low friction surfaces on helmet shells, or low friction patches on the sides. However, the rigid spherical helmet model behind the SHARP protocol is wrong in several aspects. Computer modelling (Mills et al. 2009) showed that a reduction of the helmet/road friction coefficient, below that at the head/helmet interface, did not reduce peak headform rotational accelerations. The experimental results of Finan et al. (2008) confirmed that a low helmet shell friction coefficient was not necessarily beneficial. Hence the helmet design could be changed, without necessarily benefiting motorcyclists.

Glaister (1996) argued that the simplest method to reduce the risk of head injury by rotational acceleration would be to reduce the peak linear acceleration allowed in direct impact tests. Mills et al. (2009) made the same point, and noted that a reduced impact velocity on the kerbstone anvil would allow lower density polystyrene foam liners to be used of the same thickness. The lower peak F_N in oblique impacts would cause the peak tangential force F_T to be smaller, hence reduce the contributions of both force components to the headform rotational acceleration.

11 Conclusions

The SHARP ratings do not assess the rotational acceleration performance of helmets as claimed, because headform rotational accelerations were not measured. The use of direct impact test results with a friction coefficient to calculate oblique peak acceleration is based on an unsound mechanics model, treating the head and helmet as a rigid sphere sliding on the road. Extrapolation of the helmet response, from low velocity V_N oblique impacts of the COST 327 program to much higher V_N oblique impacts, was shown to be invalid. FEA is necessary to model the large geometry changes in helmet impacts, helmet rolling on the road surface, helmet rotation on the wearer's head, and the normal force F_N contribution to the head rotational acceleration; it shows that the assumptions of the simple model are wrong.

The SHARP star ratings are based on estimates of fatalities, if all motorcyclists wore the particular helmet model. As COST 327 statistics for the frequency of different impact types were misinterpreted, oblique impacts at the Regulation 22 side impact site were over-weighted in the SHARP calculations.

The peak linear headform acceleration in an oblique impact is not a function of the total velocity V, as assumed, but of the velocity component V_N. This is the most likely reason why fatalities were overestimated by 300%.

To improve the protection of motorcyclists against rotational head acceleration, ideally headform rotational accelerations should be measured in oblique impacts with normal velocity components $V_N \geq 5$ ms^{-1}. An effective interim measure would be to reduce the peak linear acceleration in direct impact tests.

References

Aare M, Kleiven S, Halldin P. 2004. Injury tolerances for oblique impact helmet testing, Int J Crashworthiness, 9: 15-23.

Aldman B, Lundell B, Thorngren L. 1978. Oblique impacts – a parametric study in crash helmets, IRCOBI (International Research Committee on Biokinetics of Impacts) conference, 129-141.

BS 6658:1985 Protective helmets for vehicle users, British Standards Institution, London.

StClair VJM, Chinn BP. 2007. Assessment of current bicycle helmets for the potential to cause rotational injuries, Transport Research Laboratory report PPR 213, TRL, Crowthorne, Berks.

Chinn BP, Doyle D, Otte D, Schuller E. 1999. Motorcyclists head injuries: mechanisms identified from accident reconstruction and helmet damage replication, IRCOBI conference, 53-71.

COST 327 2001. Motorcycle Safety Helmets, Final report, Directorate General for Energy and Transport, European Commission, Luxembourg.

Dowdell B, Long GJ, Ward J et al. 1988. A study of helmet damage and rider head/neck injuries for crash involved motorcyclists, CrashLab Research Note 5/88, Huntingwood NSW, Australia

Finan JD, Nightingale RW, Myers BS, 2008. The influence of reduced friction on head injury metrics in helmeted head impacts, Traffic Injury Prev. 9: 483-488.

Funk JR, Duma SM, Manoogian SG et al. 2007. Biomechanical risk estimates for mild traumatic brain injury, 51st Proc AAAM (Association for Advancement of Automotive Medicine), Barrington (IL).

Gennarelli TA. 2005. Head injuries- how to prevent what, in Workshop on criteria for head injury and helmet standards, Snell Memorial Foundation, Milwalkee.

Glaister DH. 1996. Standards for protective helmets, NATO AGARD-CP-597 meeting, Mescalero, New Mexico.

Glaister DH, Hazell A, Mortimer P. 1983. Oblique impact testing of protective helmets: rationale and test method, RAF Institute of Aviation Medicine, report no. 680, Farnborough.

Goodwill SR, Kirk R, Haake SJ. 2005. Experimental and FEA of a tennis ball impact on a rigid surface, Sports Engng. 8: 145-158.

Halewood C, Hynd D. 2008. Safety helmet and rating programme (SHARP): development of the performance evaluation protocol, TRL report CPR 005.

King AI, King KH et al. 2003. Is head injury caused by linear or rotational acceleration? IRCOBI conf., pp. 1-12.

Kleiven S. 2007. Predictors for traumatic brain injuries evaluated through accident reconstruction, Stapp Car Crash J. 51: 1-34.

Mellor AN. 2006. Assessment protocol for motorcycle helmet safety performance, TRL report S0232VF. Available on web as part of next reference.

Mellor AN, St Clair VJM, Chinn BP 2007. Motorcyclists' helmets and visors- test methods and new technologies, TRL report PPR 186. available at www.dft.gov.uk/pgr/roads/vehicles/vssafety/pdfmotorhelmets

Mills NJ. 2007. Polymer Foams Handbook- Engineering and biomechanics applications and design guide, Butterworth Heinemann, Oxford, see chapter 16 motorcycle helmet case study.

Mills NJ, Gilchrist A. 2008a. Oblique impact testing of bicycle helmets, Int J Impact Engng. 34: 1075-1086.

Mills NJ, Gilchrist A. 2008b. Finite Element Analysis of bicycle helmet oblique impacts, Int J Impact Engng. 34: 1087-1101.

Mills NJ, Wilkes S, Derler S, Flisch A. 2009. FEA of oblique impact tests on motorcycle helmets, Int J Impact Engng., 36: 913-925.

Newman J. 1986. A generalized acceleration model for brain injury threshold (GAMBIT), IRCOBI conf., Sept 1986 Zurich.

Otte D. 1991. Technical demands on safety in the design of crash helmets, Proc 35th Stapp Car Crash Conf, 335-349

Roetert E, Groppel J. 2001. World class tennis technique, Human Kinetics, Champaign (IL).

Thom DR, Hurt HH, Smith TA. 1998. Motorcycle helmet test headform and test apparatus comparison, 16th Enhanced Safety of Vehicles (ESV) conference, Canada, 2310 available at www-nrd.nhtsa.dot/gov/database

UN ECE Regulation 22-05, Uniform provisions concerning the approval of protective helmets and their visors for drivers and passengers of motorcycles and mopeds, Geneva.

Zellmer H. 1993. Investigation of the performance of motorcycle helmets under impact conditions, SAE Trans, 102 part 6: 2525-2534.

Zhang L, Yang KH, King AI. 2001. Biomechanics of neurotrauma, Neurol Res. 23: 144-156.