A New Oblique Impact Test for Motorcycle Helmets

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Abstract – A new oblique impact test for motorcycle helmets is described, simulating a fall from a motorcycle on to the road surface or the windshield of a car. An instrumented headform falls vertically to impact a horizontally-moving rigid rough or deformable surface. Both the impact site on the helmet, and the vertical and horizontal velocities, can be varied, while linear and rotational accelerations of the head form are measured. The rig was used to compare a new helmet design with current helmets, which are designed to pass impact tests where the impact force is perpendicular to the helmet surface. The new design, which has a low friction layer between the shell and the liner, reduced, by up to 50%, the rotational acceleration of the head compared with conventional designs.

INTRODUCTION

Head injury is the most common cause of severe injuries in motorcycle accidents [1]. Otte et al. [2] showed that oblique impacts, with a significant tangential force on the helmet, are more common than radial (normal) impacts in motorcycle crashes. They found that the mean impact angle, between the helmet direction and the horizontal, was 28 degrees. This suggests that in a typical fall, the horizontal velocity component V_h is 3 times the vertical velocity component V_v. In comparison Harrison et al. [3] found that, for a jockey falling from a horse in a steeplechase, typically V_h is twice V_v. Otte et al. [2] found that the frontal regions and the sides of the helmets were the most frequently damaged regions . Regions close to the visor attachment points, at the sides of the helmets, were damaged in 18 %, and the chinguard in 15 % of all accidents.

In an oblique impact, a combination of radial and tangential forces on the helmet produces linear and rotational accelerations of the head. Aldman et al. [4] dropped a helmeted dummy on to a large rotating table moving at 8.3 m/s, and observed values of the peak angular head acceleration in the range 7 to 15 krad/s^2. No comparison was made with results when the table velocity was zero. In a companion paper [5], where only a headform and flexible neck were dropped, the effect of changing the sliding velocity from 2 to 17 m/s was a reduction of less than 20% in the peak linear acceleration. Since the impact site was initially on the forehead, the oval cross-section of the head/helmet meant that the centre of gravity of the head approached the impact surface as the head rotated (though they did not mention this). Their test rig was large and expensive to construct, and apparently risky (parts of the tarmac surface flew off the table).

Gennarelli et al. [6] described the most frequent brain injuries from motor vehicle accidents, causing death or long term rehabilitation, as Subdural Haematomas (SDH) and Diffuse Axonal Injuries (DAI). Bridging vein rupture can cause SDH, whereas DAI is caused by the disruption of axons in the brain tissue. These injury mechanisms have been related to rotational acceleration of the brain. Gennarelli et al. [6] concluded that SDH was generated by a short duration and high amplitude angular acceleration, while DAI was generated by longer duration in combination with lower amplitude. The proposed onset for DAI is an angular acceleration of 10 krad/s^2 in combination with a rotational velocity of 100 rad/s [7]. When the head is subjected to an oblique impact, the scalp can shear to some extent, and the exterior of the brain, 'floating' in CerebroSpinal Fluid (CSF), can move parallel to the dura (the inner lining of the skull). The motion will eventually be restrained by bridging veins, but will reduce the rotational energy transferred to the brain.

Motorcycle helmets sold in Europe must meet United Nations Regulation 22 [8], or national standards such as BS 6658 [9]. The impact tests in these measure the linear acceleration of a headform, when it and a helmet is dropped vertically from 2 to 3 m on to flat or curved rigid surfaces, that are locally tangential to the helmet surface. The test criterion in BS 6658 is that the headform linear acceleration should not exceed 300 g. In Regulation 22 the limit is 300 g, and the acceleration must not exceed 150 g for more than 5 ms. These standards contain no test that simulates a fall from a motorcycle followed by an oblique impact with the road surface. The oblique impact tests in BS 6658 ensure;

- that projecting visor mounts etc, shear off easily when there is an impact with a series of parallel bars; and
- that the tangential force on the helmet shell, when it impacts a rough flat surface, is no larger than that for typical shell materials used in 1985 (the year of introduction of the test).

The velocity normal to the impact surface is only 2.6 m/s. This test (method A) was introduced in Amendment 05 of Regulation 22. An alternative method B has a zero impact velocity (but a 400 N static force), as the helmet is resting on the rough surface, prior to the surface being moved. In neither test is the (peak) contact area between the helmet shell and the 'road' surface large enough to be typical of those in motorcycle crashes. The velocity, tangential to the helmet surface, should be typical of falls from motorcycles. At the same time, the impact velocity normal to the surface should be at least 5.4 m/s (for a free fall from a typical head height of 1.5 meter while riding). This will ensure that the shell and foam liner are significantly deformed and the contact area with the 'road' is large.

Helmets, designed to meet current standards, provide some protection against oblique impacts. Depending on the direction of the tangential force vector acting on the helmet surface, the helmet can rotate on the head to some extent. The rotation is largest when the force vector causes the helmet to rotate about an ear-to-ear axis; this rotation that can lead to helmet roll-off by inertia. It is least when the rotation is about a crown to base-of-skull axis, due to the oval shape of the horizontal section of the head. The foam liner can also shear elastically to some extent.

Motorcycle helmets contain an energy-absorbing polymer foam liner, that may be attached at a single point, or be an interference fit to a stiff thermoplastic, or fiber composite, shell. In an oblique impact, the helmet shell will transfer the tangential force component to the foam liner, which may partly transfer it to the head. We believe that helmets can be improved by interposing a low friction layer between the shell and the liner. The multi-direction impact protection system (MIPS) helmet was designed to mimic the natural protection of the brain inside the skull, by having a low friction layer between the shell and the liner. In a study by Halldin et al. [10] they subjected simplified spherical ‘helmets’ to a near-tangential impacts from a pendulum test rig. The MIPS ‘helmet’ reduced the head-form angular acceleration by up to 30%, compared to a ‘helmet’ in which the liner was glued to the shell. However, more typical helmet shapes need to be tested with a method that is a better simulation of motorcycle accidents.

The objectives of this study were to develop such an oblique impact test, and to compare the responses of conventional and novel helmets.

MATERIAL AND METHOD

Helmet modification

The 24 open-face helmets tested were from one manufacturer (Helmets Ltd of Stranraer, Scotland) (Figure 1). The helmets were manufactured with ABS thermoplastic shell and Expanded Polystyrene liners (EPS), of density 40 kg/m^3. The liner was manufactured with an outer diameter 2 mm smaller than the shell. The helmets differed at the interface between the shell and the liner (table 1).

Figure 1 Left: The liner with the protruding black rubber strips. Right: The shell front, to which the rubber strips are taped.

Table 1 Helmet constructions investigated:

Abbreviation	layer between shell and liner	at front and rear edge of shell/liner
GLUED	Unibond adhesive	None
FREE	Air	rubber strip
MIPS	low friction layer	rubber strip

The GLUED and the FREE helmet were manufactured to be two extremes of conventional helmets. Some conventional helmets have the liner glued to the shell at a small region of the crown, resulting in a relative stiff joint between liner and shell. In many other helmets the liner is an interference fit in the shell, and the liner can thereby be forced to rotate in the shell. The extremes of these two helmet concepts were modeled with the GLUED and the FREE helmet.

In the GLUED helmet a Unibond adhesive (*No-more-Nails*, from Henkel Home Improvement & Adhesive Products) was used between the shell and the liner. In the FREE helmet the shell and the liner were separated with air and attached together with a flexible joint at the bottom edge. The flexible joint between the liner and the shell, at the front and rear of the helmet, is shown in figure 1. Each consists of four 40 mm wide and 1 mm thick rubber strips, taped to the exterior of the helmet shell, and bonded to the edge surface of the EPS liner.

The MIPS helmet was similar to the FREE helmet except for a low friction Teflon film between the shell and the liner (see Figure 2). The Teflon coated low friction layer was 0.9 mm thick, and was bonded to the liner exterior. A set of tailored segments were used, so a single layer of Teflon covered the entire curved outer surface of the liner. When there is an oblique impact to the MIPS helmet, the low friction layer allows the shell to rotate relative to the liner (Figure 2). The flexible joint at the front and rear absorbs some energy, and prevents the shell rotating so far that it hits the rear of the neck. Both the FREE and MIPS helmet designs have this flexible joint.

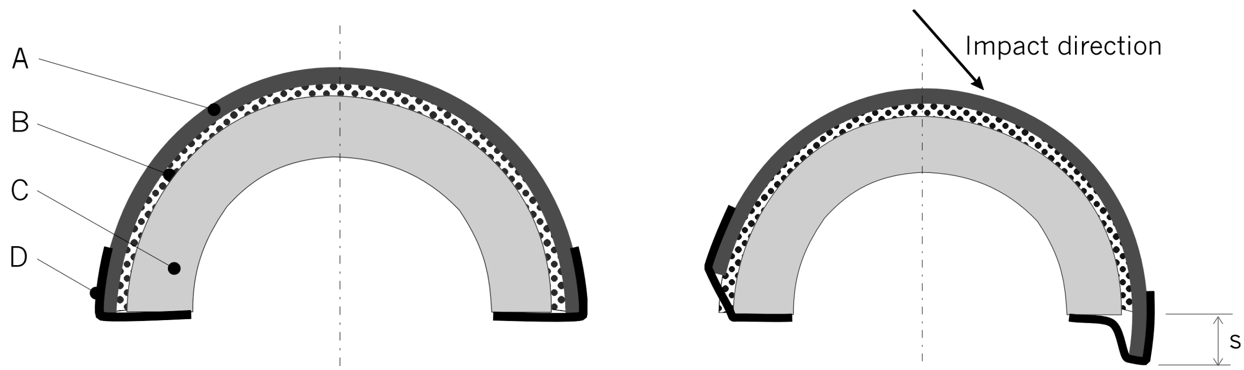

Figure 2. Left: fore and aft section of the MIPS helmet. A) shell, B) low friction layer, C) liner and D) rubber strip joint. Right: an oblique impact force causes shear deflection S of the shell relative to the liner.

The helmet liner was an interference fit to the headform, which had a 590 mm horizontal circumference. The exterior shape of the headform was very similar to the internal shape of the EPS liner. In reality motorcycle helmets contain a foam covered cloth lining, and often a horizontal band of foam to make the fit reasonable. The variation in sizes and shapes of human heads [11] means that the fit of the head to the helmet is less good. Here the helmet/headform interface was effectively tied, by omitting the comfort foam and having a liner slightly smaller than the head form. The mass and moments of inertia (measured with a torsion pendulum) of the helmets and headform are given in Table 2.

Table 2 Headform and helmet mass and angular inertia.

	angular inertia (kg cm^2)			Mass (g)
	Ear-to-ear	Nose-to-rear	Top-to-neck	
Headform	242	188	186	4362
Helmet GLUED	85	76	90	825
Helmet FREE	88	79	92	895
Helmet MIPS	92	84	97	960

The Oblique Impact Test

The test rig, outlined by Harrison et al. [3], was completed. A free falling instrumented headform impacts a horizontally moving steel plate (Figure 3) which is 0.5 m long, 0.15 m wide and 10 mm thick. The plate is moved by a Rexroth Mecman pneumatic cylinder of 1 m stroke, powered by Nitrogen gas. It rests on flat PTFE bearings, which are supported on horizontal steel surfaces, and is decelerated at the end of its stroke by ACE shock dampers. A rough road surface was simulated by grade 80 SiC grit grinding paper, bonded to the steel plate. For the simulation of a fractured windscreen, a 25 mm thick layer of 20 kg/m^3 density extruded polystyrene foam was clamped at the edges to the steel plate.

While the helmet falls vertically, its position is maintained by a U-shaped aluminum frame. The helmet moves away from the frame at time of impact (Figure 4). The following parameters could be varied: horizontal plate velocity, vertical helmet velocity, impact surface stiffness, coefficient of friction between the impact surface and the helmet, and the initial helmet position.

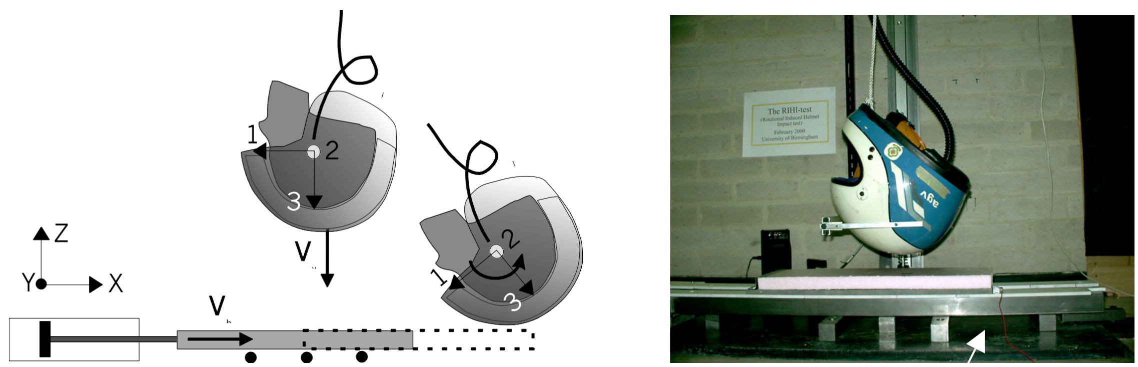

Figure 3. Left: helmet 123 and laboratory XYZ axes. V_h is the plate horizontal velocity and V_v the helmet vertical velocity. Right: test position A illustrated with a full face helmet.

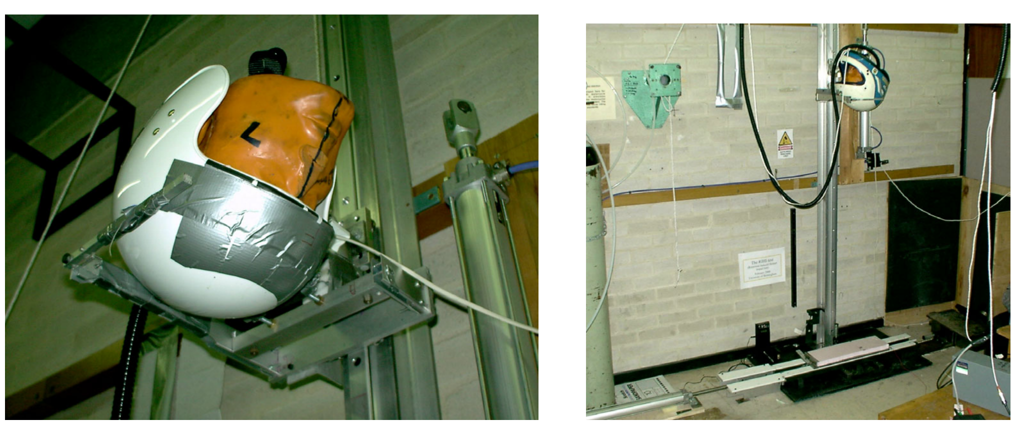

Figure 4. A helmet in position in the frame, attached to a vertical monorail. Left: Test F. Right: Test A.

A dummy headform (Ogle Ltd, Letchworth, U.K.) of head circumference 590 mm was used. The cast hollow aluminium headform is coated with a layer of PVC plastisol, and has internal vibration damping elements added. Its linear acceleration, and angular velocity about one axis, were measured at its centre of gravity, using a Kistler triaxial linear accelerometer model 8792A and a single axis magnetohydrodynamic angular rate sensor ARS-01 from Applied Technology Associates, Albuquerque, New Mexico. The angular rate sensor was oriented so that its rotation axis was parallel to the laboratory Y axis (Figure 3) about which the helmet rotates. The signals were sampled at 1 kHz and recorded with 12 bit accuracy. The magnitude of the total linear acceleration vector was computed from the 3 components.

The horizontal velocity V_h was restricted by the gas pressure and the size of the pneumatic cylinder. The maximum drop height of 3 meters allowed a maximum vertical impact velocity V_v of 7.67 m/s or 27.6 km/h. The initial height was in this study chosen to 1.5 m and V_v was measured just before impact with a photo-gate timer to 4.8-5.2 m/s. The steel plate was accelerated by a pneumatic cylinder (Figure 5) to speeds up to between 4.6-6.3 m/s. Its horizontal velocity was measured by integrating the signal from an Endevco linear accelerometer attached to the plate. A typical velocity vs time history (Figure 6) shows that the plate decelerates during the helmet impact. The tests were filmed using two Canon high-speed digital cameras, taking 1000 pictures per second.

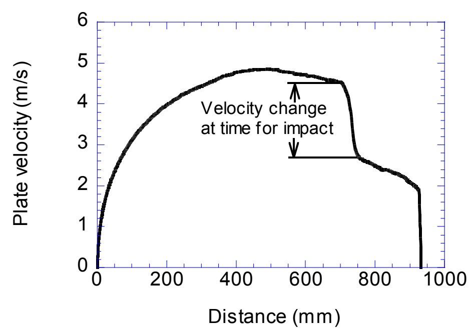

Figure 5. Plate velocity as function of sliding distance.

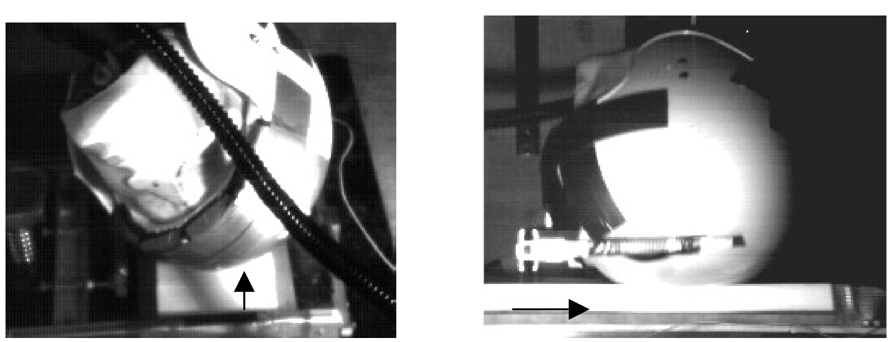

Figure 6. Views of test C with the steel plate covered with foam. (left: along close to the X axis (11ms after initial impact), right: along the Y axis (5ms after initial impact). The black arrow shows the plate velocity.

Seven different test configurations were investigated (Table 3). In tests B and F the plate is stationary. The orientation of the helmet at initial impact was defined by stating which of the headform 123 right-handed axes was along each of the laboratory XYZ axes (Figure 3). For example, test C (Figure 6) has the headform negative 1 axis along the laboratory X axis, the 2 axis along Y and the negative 3 axis along Z, so is described as (-1,2,-3). The helmet was then rotated by 45 degrees about the X-axis, so the final position is given in Table 3 as (-1,2,-3) [45,0,0]. It means that the impact site is midway between the crown and the ear of the helmet, and the tangential force acts towards the rear of the helmet.

Table 3. Description of impact site and direction for the oblique tests.

Test	Helmet axis direction in XYZ-system	Helmet rotation around which ZYX-axis (deg)	Figure No	Impact site	Tangential force direction relative to helmet
A & B	(-1,2,-3)	[0,0,0]	4	Crown	Rearwards
C	(-1,2,-3)	[45,0,0]	6	Midway from crown to side	Rearwards
D	(2,1,-3)	[15,0,0]	9	Crown	Lateral
E	(3,2,-1)	[0,0,0]		Forehead	Vertical
F & G	(1,-2,-3)	[0,30,0]	5	30 deg from crown towards front	Forwards

RESULTS

Figure 7 shows the results of all helmets tested in test type A, with the steel plate covered with grinding paper. In test A (grinding paper) three helmets of each design were tested. Average curves were calculated from each test series, Kaleidagraph software [12], after positioning the curves so that the time for maximum acceleration coincided for each helmet type.

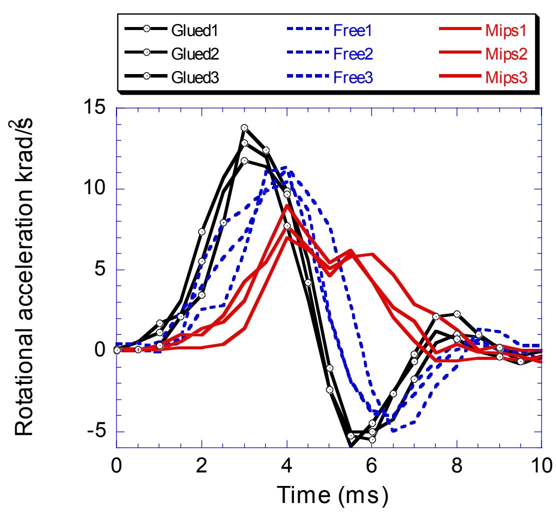

Figure 7. Rotational acceleration as function of time for all helmet testet in test A with the steel plate covered with grinding paper.

Figure 8 shows the headform angular and linear acceleration as function of time for test A. The curves show the average result calculated from the output data. In test A (grinding paper), the MIPS-helmet reduces the peak angular acceleration by 28% and 39% respectively, compared with the FREE and the GLUED helmet. When the steel plate was covered with foam the reduction was 20% compared with the FREE and GLUED helmets, Figure 8 (top-right).

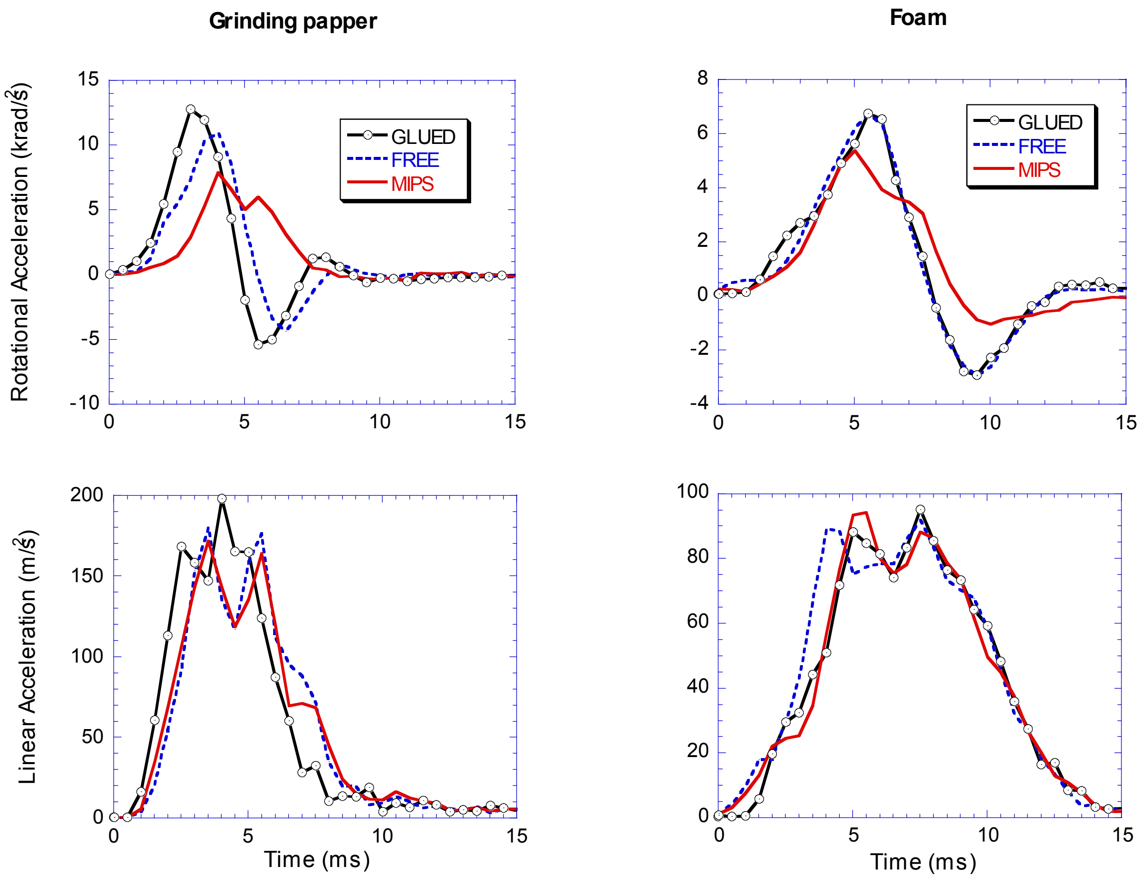

Figure 8. Test A. Comparison of rotational (top) and linear accelerations (bottom) for GLUED, FREE and MIPS helmets impacting rough rigid (left) and foam surfaces (right), at $V_h = V_V = 5$ m/s.

The acceleration results (Table 4) show that the MIPS-helmet reduces the angular acceleration significantly, in all oblique impact tests, compared to the other helmet designs; for example in test F the rotational acceleration is reduced by a factor 2 compared with the GLUED helmet.

In the perpendicular impact tests B and G (Vh=0), the peak linear acceleration for the GLUED helmet is slightly lower than for the other two helmet designs, see Figure 9. This suggests that the extra helmet stiffness may be an advantage in such tests. Comparing the perpendicular with the oblique impact tests (A vs B and F vs G) for the GLUED helmet, the peak linear acceleration is approximately the same. However, making the same comparison for the FREE and MIPS helmets, there is a 10-25% higher peak linear acceleration in the perpendicular tests. The double peaks in the linear acceleration traces are due to a linear oscillation of the shell mass on the EPS liner, which acts as a spring.

Table 4. Oblique impact test results. The number in brackets () is the standard deviation.

Test	Helmet Type	Horizontal plate velocity (m/s)	Rough grinding paper surface: No. of helmets tested	Rough grinding paper surface: Max angular accel krad/s²	Rough grinding paper surface: Max linear accel. g	Rough grinding paper surface: Angular velocity change (rad/s)	Foam surface: No. of helmets tested	Foam surface: Max angular accel krad/s²	Foam surface: Max linear accel. g	Foam surface: Angular velocity change (rad/s)
A	GLUED	5.0	3	12.8 (1.5)	192 (10)	29.0	2	6.7 (0.2)	95	25.4
	FREE	4.9	3	10.9 (0.5)	186 (13)	26.9	2	6.7 (0.3)	93	24.3
	MIPS	5.0	3	7.9 (1.0)	172 (17)	24.0	2	5.3 (0.6)	100	22.5
B	GLUED	0	1	3.0	197	-	1	1.0	114	-
	FREE	0	1	4.9	245	-	1	3.2	122	-
	MIPS	0	1	4.8	227	-	1	1.4	104	-
C	GLUED	4.8	1	16.3	212	30.2	0	-	-	-
	FREE	5.0	1	13.4	190	28.7	1	8.0	134	24.4
	MIPS	5.0	1	8.6	209	23.0	1	5.7	118	24.2
D	GLUED	5.0	1	13.1[a]	204	25.5	1	7.6	121	28.3
	FREE	5.0	3	12.3 (1.9)	210 (9)	24.0	1	7.8	116	25.2
	MIPS	5.0	3	7.6 (0.1)	209 (8)	21.5	1	5.9	119	23.5
E	GLUED	5.0	1	6.6	170	15.1	1	3.6	109	16.6
	FREE	5.0	1	3.4	149	13.0	0	-	-	-
	MIPS	5.0	2	1.5 (0.3)	166 (36)	6.5	0	-	-	-
F	GLUED	6.3	3	12.6 (2.1)	187 (19)	34.2	0	-	-	-
	FREE	6.3	4	11.5 (0.8)	168 (12)	31.5	0	-	-	-
	MIPS	6.3	4	6.3 (1.0)	174 (19)	27.5	0	-	-	-
G	GLUED	0	1	1.4	185	-	0	-	-	-
	FREE	0	1	2.6	195	-	0	-	-	-
	MIPS	0	1	1.3	192	-	0	-	-	-

a: The liner escaped from the shell.

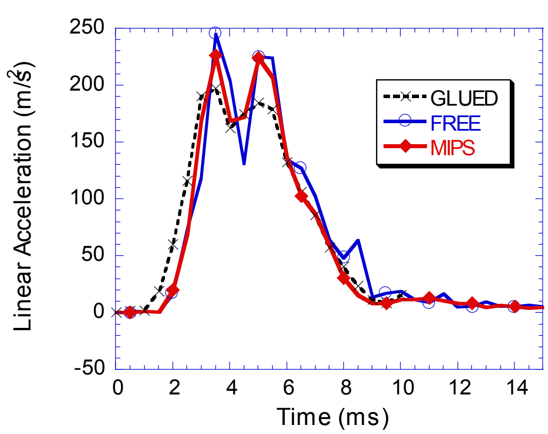

Figure 9. Test B. Comparison of rotational for GLUED, FREE and MIPS helmets impacting rough grinding paper, at $V_h = 0$ m/s and $V_V = 5$ m/s.

The headform rotational and linear accelerations (Figure 10) were normalized to have unit peak values, so that the times of the peaks could be compared. For the GLUED helmet, the rotational acceleration oscillation has a larger magnitude and slightly longer period than the linear acceleration oscillation. For the MIPS helmet, the rotational acceleration signal appears to follow the linear acceleration signal. It is unlikely that the shell can oscillate rotationally on the EPS liner, and the simplest explanation is that there is a near constant coefficient of friction at the shell/liner interface of the MIPS helmet.

The tests with the paper surface give higher angular and linear acceleration peaks than those with foam surface. However, the angular velocity changes seemed to be independent of the impact surface. This probably indicates that helmet sliding, relative to the plate, had ceased before the end of helmet contact with the plate. At this stage the helmet surface is rolling on the plate; Figure 11 shows frames from the high-speed camera. The helmet hits the plate in the middle, and in the second frame the helmet has indented the foam, which leads to rotation (frame 3). The films of each test were examined to confirm that the initial impact position was as expected.

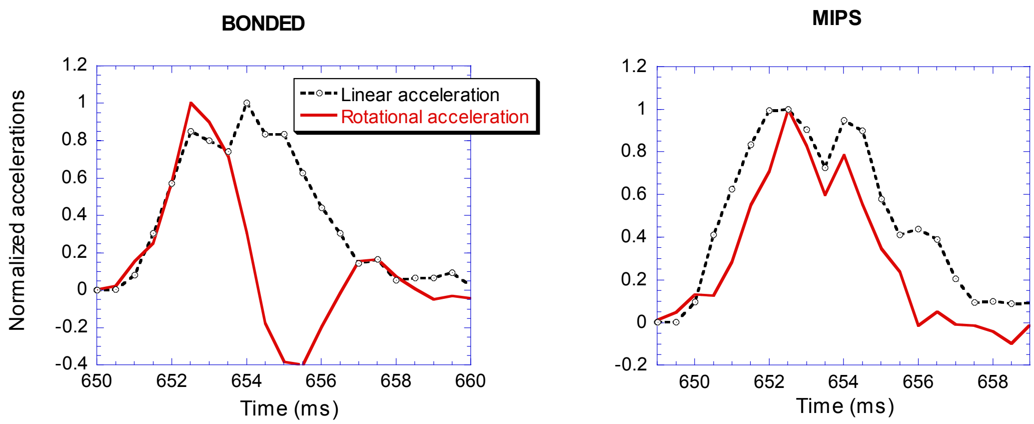

Figure 10. The figure shows the linear and rotational acceleration normalized against the respective peak accelerations.

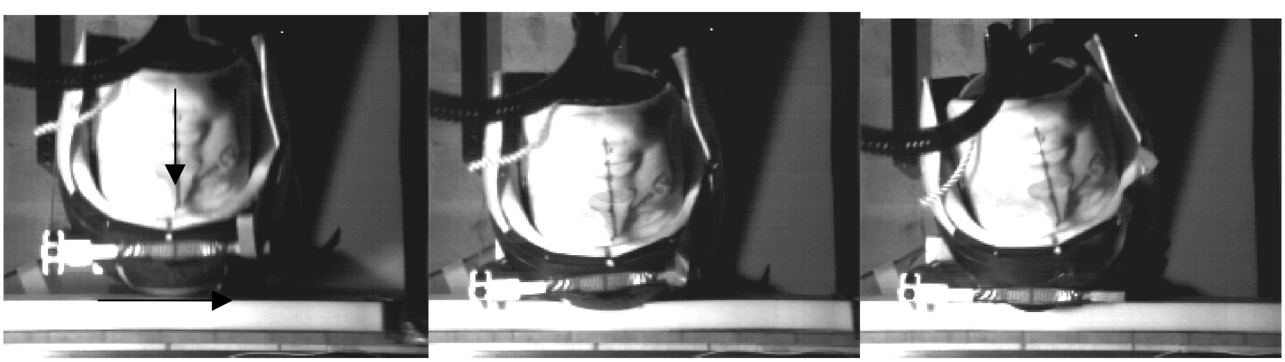

Figure 11. Test D impact on a foam surface. The time interval between the frames is 9 ms.

DISCUSSION

The aim was to design an oblique testing method for motorcycle helmets. It was possible to approach but not replicate exactly the median impact described by Otte et al. [2]; the side of the helmet making an oblique impact at 28 degrees to the horizontal at a speed of 44 km/h. In test C,

(Figure 8) the impact site was towards the side, the impact speed was 29 km/h and the impact angle was 38 degrees. These conditions are close enough to Otte's scenario to conclude that the MIPS-helmet could significantly reduce the peak angular acceleration of the head. If the helmet design can reduce angular acceleration for an oblique impact at 38 degrees, it should be more effective for smaller impact angles. Although lower impact speeds result in smaller shell and liner deformations, Otte et al. [2] showed that AIS (abbreviated injury scale) 2+ injuries occurred in accidents below 20 km/h. Therefore, the tests are relevant to injury-causing crash types. Future tests will be made with higher impact energies.

The measured headform angular accelerations were up to 15 krad/s^2 and the angular velocity change up to 36 rad/s. These compare with an angular acceleration of 10 krad/s^2 and a rotational velocity change of 100 rad/s, proposed by Margulies and Thibault [7] as the injury threshold for DAI. Our tests probably would not have produced DAI injury. However, by increasing the horizontal plate velocity, it should be possible to impart headform angular velocity changes above 100 rad/s. For similar velocity oblique impacts on the steel plate, the peak angular acceleration was greater with the foam surface than it was with the rough paper surface. Therefore, in a test for protection against DAI, a foam impact surface could be used. However a foam surface, 25 mm thick, cannot fully simulate the deformation of a fractured laminated windscreen, which can deform by 200 mm or more.

The form of the rotational acceleration versus time trace for the glued helmet (Fig. 7) is similar to that for typical tangential force vs time traces for BS6658 oblique impact tests; the acceleration becomes negative in the latter parts of the trace. Mills and Gilchrist [13], discussing such traces, concluded that there was a rotational oscillation of the helmet shell on the deformable EPS foam. The negative angular acceleration peak in Figure 7 is smaller for the FREE and MIPS helmets. In real life, it is likely that sliding at the comfort foam/hair/scalp interface will produce a similar effect to that of the MIPS helmet, so reverse angular accelerations of the head are unlikely.

It is reassuring that the effect of the horizontal velocity component on the peak linear headform acceleration, for tests with the same perpendicular impact velocity, was to slightly reduce the peak linear acceleration for the FREE and MIPS helmets. The national and European helmet standards assume that the horizontal velocity component has no affect on the peak g value. Mills and Gilchrist [12] showed this for a slice of a bicycle helmet on a constant radius headform. However, in tests with a complete helmet, if the center of mass of the headform was nearly stationary, it would move towards the road surface if the helmet rotates in a direction in which the headform radius decreases (or move away, if the radius increased). It seems that the headform rotation is too small during the contact period for this effect to be significant.

This study only considered one helmet size and one open face helmet model. There was no comfort foam inside the helmet, and the headform had neither scalp nor hair. The soft polyurethane foam will rapidly compress to a near-solid in the impact, but the scalp and hair will probably increase the possible rotation of the helmet relative to the head. Therefore future tests should consider a greater range of helmet types and fit.

CONCLUSION

An oblique testing method for motorcycle helmets has been constructed, that is durable and reproducible, that simulates typical falls to the road surface. It provides greater impact deformation of the helmet than the *oblique impact* tests in BS 6658 and Regulation 22/05, which are only intended to test helmet projections. The used test rig will be valuable in the search for helmets, which minimize rotational trauma. It has already shown that the MIPS helmet reduces the peak headform angular acceleration, independent of the initial position of the helmet in the test.

ACKNOWLEDGEMENT

The authors are grateful for Helmets Ltd of Stranraer, Scotland for assistance with the supply of helmets, and to the instrument loan scheme of EPSRC for the loan of the high speed camera. We also wish to thank the Länsförsäkringar Corporation Research Found and NUTEK, Sweden for financial support.

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