Improvements in the Design and Performance of Motorcycle Helmets

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1. Introduction

The design of motorcycle helmets in the U.K. has recently changed as a result of the implementation of a new British Standard BS6658 (1) in April 1986. This introduced a number of new performance requirements, for example a test for the effectiveness of the retention system, oblique impacts on the shell, and impacts on the chin bar. Because these tests must be performed quickly and reproducibly, they are relatively simple. Thus the helmet retention test is carried out with a headform of a single size, whereas the size and shapes of heads are known to vary. In order to provide better data for the design of helmet retention systems we measured head size parameters that are directly related to helmet fit and retention.

In the helmet impact tests the performance criterion is that the peak acceleration should not exceed 300 (g). The actual performance level is not published, and valuable information on the mechanics of the impact is wasted. Consequently we carried out computer integrations of typical acceleration data to yield force-deflection data for the helmet structure, which can be related to the dimensions and materials used. Also, to relate helmet performance more directly to the parameters used in car-crash testing, we measured the Head Injury Criterion using an instrumented dummy wearing a helmet.

2. Head Measurements Related to Helmet Retention

2.1 Head size survey

Previous surveys of head sizes (2,3) have used RAF personnel, who may not have been typical of the general population. The measurement methods were relatively slow, either using tape and calipers alone (2), or these plus photogrammetry (3). The measurements were relative to anatomical features such as the ear opening or the lower edges of the eye sockets, and did not consider the way in which a helmet would fit on the head. Consequently we designed a measurement rig based on the subject wearing a helmet, so that the measurement points related to helmets.

The starting point for the measurements is the headform (Fig. 1) described in BS 6489 and called up in the BS 6658 motorcycle helmet standard. The protective cover of the helmet must extend downwards at least as far as the horizontal AA' plane (and further at the sides). The distance y from the top of the headform to this AA' plane varies with the circumference of the headform as shown on the figure. The AA' plane at the front is meant to correspond to the brow ridge crest.

Helmet manufacturers normally use two sizes of hard polystyrene foam liners inside a single size helmet shell. The range of 4 or 5 sizes are then made up by adding a 25 mm wide band of softer foam, with its lower edge on the AA' plane, of varying thickness.

We measured heads

a) on a horizontal plane that is 86 mm below the top of the head (vertex). This establishes the head sizes somewhere near the top of the horizontal sizing band. Fig. 2 shows that the 8 measurement points are nominally at 45^o angular separation.

b) on the vertical (mid sagittal) plane that passes through the front and rear points 1 and 5 of set a). These points are at 45^o angular separation. There is also point 12 that is 30^o below the horizontal plane, which measures the nape of the neck. Point 10 is a fixed bolt which establishes the distance from it to the horizontal plane.

19 mm plastic discs are forced to contact the head with a pressure of approximately 200 mm Hg, by using a small pump to pressurise 10 ml medical syringes. A linear potentiometer then senses the position of the disc. The pressure is sufficient to compress the hair fully. The recording time per subject is about 1 minute. The data is fed into a BBC microcomputer which calculates the 12 radial distances H_i from the measurement pads to the centre of the head. The length, width and two diagonal distances on the horizontal plane can then be calculated. To aid computation of the circumference, the shape of the horizontal section of the head is then drawn using the following assumptions

(i) The profile is symmetrical at the front, left side, right side and rear, i.e. $dH/d\theta = 0$ at $\theta = 0, 90, 180, 270^o$

(ii) The profile consists of three terms

$$H = A + B \cos 2\theta + C \cos 4\theta$$

being respectively circular, elliptical and square terms. The values of A, B and C are determined separately for each quadrant.

There was insufficient time or money to build an equivalent automated helmet measurement rig. Consequently a simple manual rig was constructed using 1 mm pitch metric bolts located on vertical and horizontal 6mm polycarbonate plates. The measurement positions correspond exactly with those of the head measuring rig.

Three head surveys were carried out, namely (a) a large (469) sample of students (and staff) from Birmingham University, (b) a smaller sample (47) of motorcycle riders to check that the sample of students had heads of the same type as that of motorcycle riders, and (c) 18 of the standard headforms at the BSI test house at Hemel Hempstead.

When histograms of the individual size parameters were plotted, they appear to have a Gaussian (normal) frequency distribution. Table 1 compares the data with that of the RAF survey.

Our results differ from those obtained for RAF aircrew (2) for two reasons; firstly their circumference measure was a maximum one whereas ours is at a section 86 mm below the vertex, secondly the higher pressures at the 8 measuring points in our survey will compress the hair more than will a tight measuring tape over the hair. Consequently it is impossible to establish if the RAF aircrew population has a mean head circumference that is statistically different from that of the general population.

The maximum diagonal measurement from the chin to the rear of the head was measured with calipers. To be certain that 95% of the population can get their chins into a full face helmet the helmet distance must exceed $x + 2\sigma$ or 272 mm. Some helmet measurements performed here show that most helmets have a chin bar interior that is more than 270 mm from the back of the helmet liner. This then means that for the majority of motorcyclists the chin bar will not interact with the chin in a way that limits forward rotation of the helmet.

Table 1 Head dimensions in mm

Quantity	This survey n = 516 mean $\bar{x}$	std. dev. σ	$(\frac{\sigma}{\bar{x}})\%$	RAF Survey (2) n = 2000 mean $\bar{x}$	std. dev. σ
Circumference	555.9	15.5	2.8	567.7	13.6
Length	195.0	7.0	3.6	199.0	6.4
Diagonal 1	179.8	6.1	3.4		
Diagonal 2	175.9	6.2			
Breadth	155.6	6.1	3.9	157.8	5.4
Indent at nape	-2	4			
Max. diag. to chin.	250	11	4.4		

The quantity H_5-H_{12} measures the degree to which the back of the head deviates from a sphere, between the back of the head and the nape of the neck. Table 1 shows that the mean 'indent at the nape' is -2mm, so the average head is nearly spherical at the rear, with a slight outwards deviation at the nape. The roughly spherical shape of the vertical section of the back of the head and the range of 'inset at nape' values means that any retention system that grips the nape of the neck cannot involve a hard polystyrene foam. Other possibilities are an adjustable webbing nape strap, or a flexibile but relatively inextensible cloth nape collar filled with polyurethane foam. Both features have been used to improve the retention performance of helmets.

Figures 3 show two of the cross plots of pairs of size parameters. Superimposed on the 516 data points are the best straight lines established by linear regression analysis. The equation of this line and the correlation coefficients for the data are given in table 2. The other dashed line shown on each graph is the regression line for 18 headforms. In every headform graph the data points fell almost exactly on the line and the correlation coefficient exceeded 0.99.

Table 2 Correlation between pairs of variables

Variable y	Variable x	Correlation Coeff. r (RAF)	Regression Line Parameters A(mm)	B
Circumf.	Length	0.79 (0.77)	213.2	1.758
Circumf.	Breadth	0.66 (0.55)	286.4	1.682
Circumf.	Diagonal 1	0.82	182.8	2.075
Length/Breadth	Length	0.58	0.277	0.00501
Breadth	Length	0.19 (0.20)	123.5	0.164
Diagonal 2	Diagonal 1	0.46	91.6	0.469

The regression line is $y = A + Bx$

Table 2 shows that the correlation coefficients are similar to those found in the RAF survey. Values of r exceeding 0.6 suggest that the length, the breadth and the diagonal measure all contribute to the circumference, whereas the value below 0.2 for breadth versus length suggests that these parameters are not related. The length/breadth parameter is a measure of the 'sphericalness' of heads. It was found that shorter heads are more spherical. In contrast the BS and other headforms have an almost constant L/B ratio.

Fig. 3b shows that the majority of people have a longer front-right to rear-left diagonal (the dashed regression line for the headforms is very close to D1 = D2). Table 1 shows that the mean value of D1 is 3.9 mm larger than the mean value of D2. It is possible that this difference is due to the preponderence of right handed people; it would be interesting to find out.

2.2 Helmet fit

A preliminary analysis of helmet fit has been based on two sets of helmet sizes. The first is based on 4 BS headforms, so represents the fit at the headband of the range of 4 sizes sold by most UK manufacturers. The second range is a hypothetical one based on the survey data.

Table 3 (Idealized Helmet Sizes (in mm)

A. Based on measured B.S. Headforms

Size	Circumf.	Length	Breadth	Diagonal	L/B
1	540	190	148.7	173.3	1.28
2	560	195	153.9	181.7	1.27
3	580	203.2	164.4	189.2	1.24
4	600	210.5	167.5	194.8	1.25

B. Wide and narrow fittings based on the survey data.

1	Short narrow	195	156	180	1.25
2	Short wide	195	168	187	1.16
3	Long narrow	209	156	187	1.34
4	Long wide	209	168	192	1.24

A computer program then sorted through the 516 head sizes on file and allocated to each the smallest helmet for which the head length, breadth and diagonal were less than the corresponding helmet dimensions. Figure 4 shows the histograms of the number of helmets needed of each size. Discussions with U.K. manufacturers indicated that size 3 helmets sold the most, followed by sizes 2 and 4, with size 1 least, so the first histogram is realistic even if the absolute numbers cannot be checked.

The computer program also calculated the average gap between the chosen helmet and the head size, by averaging the quantity FIT = $L_i + B_i + D_i - L - B - D$, where the subscripts refer to the helmet dimensions. The parameter FIT was 26 mm for range A and 24 mm for range B. If the gap were uniform around the head this would indicate an average gap of 4 mm everywhere. However, in terms of helmet retention the gap at the front and rear of the helmet should be most important.

3. Impact Protection

3.1 Current British Standard Impact Tests

BS 6658 sets performance criteria for a wider range of impact sites than in earlier standards, and addresses itself to both linear and angular acceleration as potential causes of injury. However the three tests developed differ considerably in type and in the performance criteria.

Table 4 Impact tests in BS 6658: 1985

Acceleration	Site	Rig	Velocity ms^{-1}	Criterion
Linear	on or above AA'	falling headform, head cannot rotate on 'neck'	7.5	<300 g
Linear	chin bar	falling flat 5 Kg striker, back of helmet on rubber block	7.0	<300 g
Angular	Any	falling full headform (no neck) onto surface at 75^{o} to horizontal	10.0	F <4 kN Impulse < 28 Ns

In the direct impact tests the headform cannot rotate, but in the oblique impact test it does rotate freely. In the latter the limit for the force component tangential to the helmet shell is set at such a high level that it would take an unconventional helmet shell material or shape to fail the test. When the helmet is struck on the chin bar, the fact that the back of the helmet is supported means that energy can be absorbed elastically by the deformation of the shell shape until the chin bar foam contacts the headform chin. We have estimated, by measuring the shell stiffnesses of various helmets, that between 10% and 40% of the 125 J impact energy is used to deform the shell shape.

3.2 Helmet shell materials and performance

There are practical limitations on the mass of a helmet that is acceptable, and on the thickness of the energy-absorbing foam liner. This then places an upper limit on the impact speed (or kinetic energy of the head) at which the helmet can be expected to work. Computer analysis of the striker acceleration trace in a fixed headform impact test (4) can provide a force versus helmet deflection graph like Figure 5. Assuming for a moment that head injuries can be related to the peak acceleration measured, then the force must not exceed a particular level, for instance 10 kN equivalent to 200 g acceleration of a 5 kg head. The forces rise rapidly as the deflection of the liner approaches 80% of the liner thickness, as the cell walls in the foam begin to come into contact. The area under each graph is the same being equal to the impact energy of 125 J. If the impact energy had been only slightly higher, say 150 J, the peak 'g' levels would well above 300 g.

Accidents occur at a variety of speeds, with the majority being low speed 'minor' accidents. A single performance criterion at a fixed speed is not the best way to compare helmets. An integration of the force vs deflection curve (Fig. 5) provides a curve of peak force F_m versus the impact energy supplied so far. Such curves are compared in Figure 6 for a helmet with a thermoplastic ABS shell and one with a 'Kevlar' fibre reinforced thermoset shell (5). At impact energies less than 50 J the ABS helmet produces a lower peak force, but the situation is reversed for higher energy impacts. The difference relates to the mechanisms of deformation; the lower modulus thermoplastic buckles inwards elastically whereas the fibre reinforced shell is much stiffer and delaminates as it deforms. Another reason for preferring fibre reinforced shells in severe accidents is that they are unlikely to shatter; although recent studies (6) show that the best grades of thermoplastic are also safe in this respect.

The different force versus energy curves of the thermoplastic and composite helmet shells provides a possible explanation of some motorcycle injury statistics (7); there is a statistically significant correlation between the severity of head injuries and the helmet shell material, with GRP helmets being correlated with more severe injuries. Figure 6 provides a possible explanation, since the majority of reported accidents involve minor injuries.

3.3 Trend in impact protection revealed by impact tests on a dummy

The head, neck and torso of an Ogle OPAT dummy were mounted on a wheeled carriage, and the head instrumented with two triaxial accelerometers. A pendulum then impacts the helmet in a horizontal direction, at the level of the AA' plane. Although this test rig was not primarily designed to simulate accidents to motorcyclists it provides several features lacking from the BS 6658 tests.

i) The head is connected to a torso. Although the impact is initially directed towards the centre of gravity of the head the neck causes the head to undergo angular acceleration. The contact point between the striker and the helmet shell moves as the head rotates, so a larger area of the helmet contributes to energy absorption.

ii) The helmeted head of mass m_h is impacted by a striker of a finite mass m_s. This raises the question of the impact conditions needed to provide an impact of equal severity to that in BS6658. The 'equivalent impact enery' in BS5361 is the kinetic energy dissipated up to the point where the striker and headform have an equal velocity, this being $m_s/(m_s+m_h)$ times the initial kinetic energy of the striker. In reality not all this 'equivalent impact energy' is dissipated; some of it is stored and returned in the rebound.

iii) There are energy losses in the 8 mm thick layer of plasticized PVC, which covers the head. These may partly simulate the protection afforded by the hair and scalp of a rider.

The head was impacted in various directions with a pendulum impact device, and the resulting linear and angular acceleration vectors computed. In an attempt to generate data that relates to car-crash testing, the Head Injury Criterion (HIC) was calculated from the time average of the magnitude of the linear acceleration $\underline{a}$ (measured in 'g')

$$HIC = \bar{a}^{2.5} (t_2 - t_1)$$

where $\bar{a} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt$

A comparison of the peak acceleration a_{max}, the peak rotational acceleration and the H.I.C. was made for impacts of increasing severity on a number of sites.

At this stage in the research the following results have emerged:-

Although the bending stiffness of the rubber neck of the dummy is about 10 times that of a human neck this does not influence the size or shape of the main acceleration peak, which occurs before the neck has deflected sufficiently to provide a significant restoring force. This has been shown using a development of a 1-dimensional mass and damped spring model (8).

Changes in the design of U.K. manufactured helmets over the years have possibly reduced the protection afforded to the wearer in minor accidents. The great majority of motorcyclists are currently wearing helmets to BS 2495 or 5361, whereas a small % wear 10 + year old helmets to BS 2001, and the new BS 6658 helmets are only now appearing on the market. Blows of 50J and 60J effective energy were imparted on the sides, front and back of the helmets. The table gives results for the 50J blows.

Table 5 Side and front impacts on helmets of different ages

Standard	Type	PS foam liner Thickness at side	Density Kg m^{-3}	linear accel. g	rotation rad s^{-2}	HIC
BS 2001	Open face	20 mm	47	57, 127 (67, 75)	1300, 2700 (600, 1400)	88, 257 (116, 128)
BS 5361	Open face	22 mm	87	62, 64 (68, 90)	1400, 1600 (600, 1100)	75, 98 (135, 186)
BS 6658	Full face	27 mm	72	93, 98 (82, 92)	2300, 2400 (700, 1000)	154, 155 (144, 184)

*The bracketed figures are for side impacts, the others for front impacts.

All the helmets had thermoplastic shells, but the polystyrene liners have become thicker and slightly denser, with the requirement to meet more severe impact tests.

The reasons for the slight increase in the maximum 'g' level or HIC is found by examining the shape of the acceleration traces. Fig. 7 shows that this can vary from an inverted V to a steep sided plateau, the latter being for an older helmet. Using the approximation that the striker acceleration is $-m_h/m_s$ times the headform acceleration, and that the head rotation is negligible, a double integration of the difference between the striker and headform acceleration gives the distance between the striker and the headform. The load-distance curve shows a clear yield point for the older helmet (Fig. 8) compared with a linear loading curve for the newer one. The constructional differences are that the older helmet has a lower density foam liner with a lower compressive yield stress, and there is a rigid polyurethane foam collar below the polystyrene foam in the new helmet, but only soft 'comfort' foam in the old one. Since the impact site overlaps the lower edge of the polystyrene foam, the edge will tend to be crushed more if there is no support from rigid foams at lower levels. Both factors help to reduce the HIC with the older helmet. However it is expected that the relative ranking will be reversed for higher impact energies. When the deflection in Fig. 8 is equal to the thickness of foam inside the helmet the acceleration will rise rapidly to levels above 300 'g'. Calculations from acceleration traces for fixed-headform impacts showed that peak accelerations of 230 to 280 g corresponded to HIC's of 1500-2300.

The values of the peak rotational acceleration are small compared with the estimated threshold of 4500 rad s^{-2} at which concussion or other injuries will occur (9). Consequently for this type of impact, rotational acceleration of the head is unlikely to be the main injury mechanism.

5. Discussion

Investigations of motorcycle accidents have in the past revealed that helmets were failing to be effective for certain types of impact, or were coming off in accidents. BS 6658 includes new performance requirements that force manufacturers to address themselves to these design aspects. These are effective short term remedies. In the long term a different range of helmet sizes may provide better helmet retention for the variety of human head shapes. Similarly impact test criteria would ideally be linked to clearly defined injury criteria, using a realistic anthropometric dummy for testing. In the meantime there is a need for an accident survey of the effectiveness of the new helmet designs. The laboratory tests described here could then assess some measures of the accident severity.

Acknowledgements

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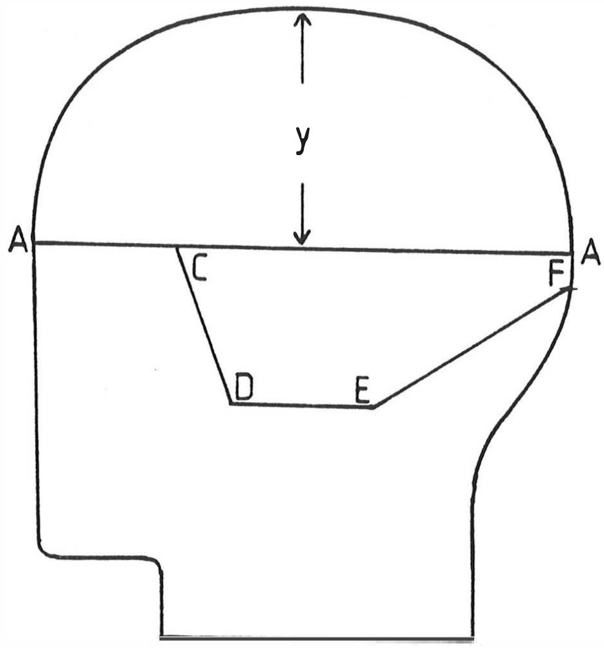
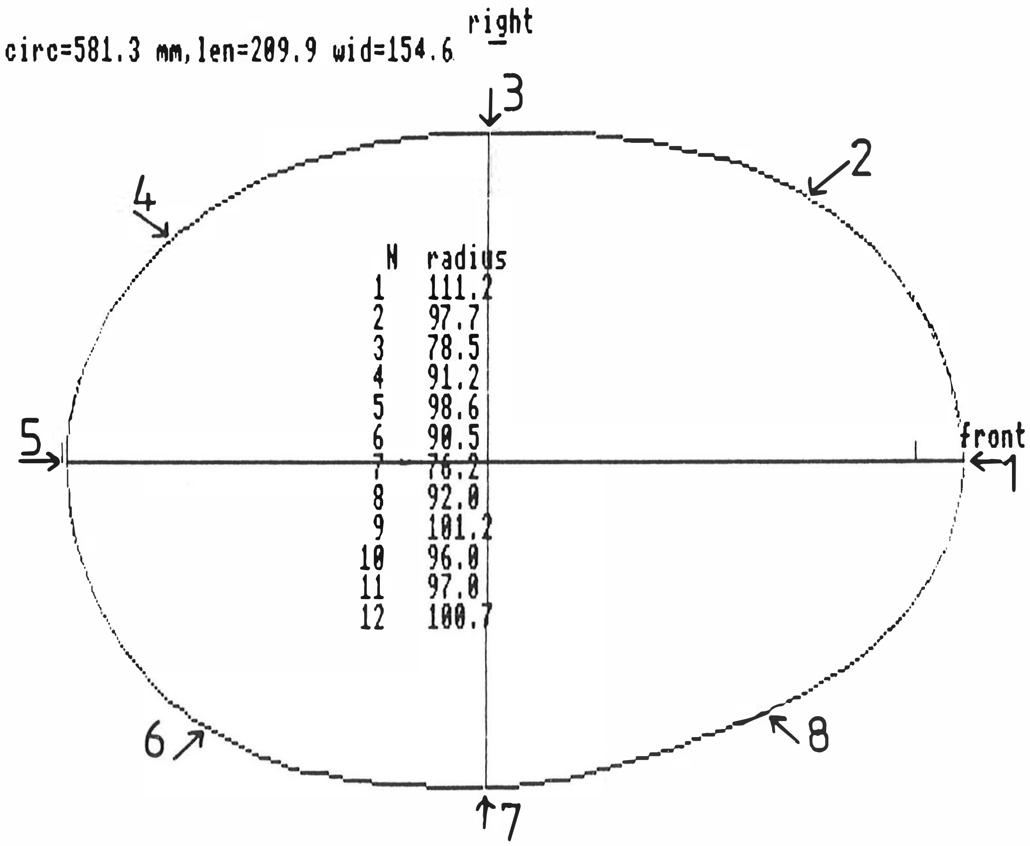
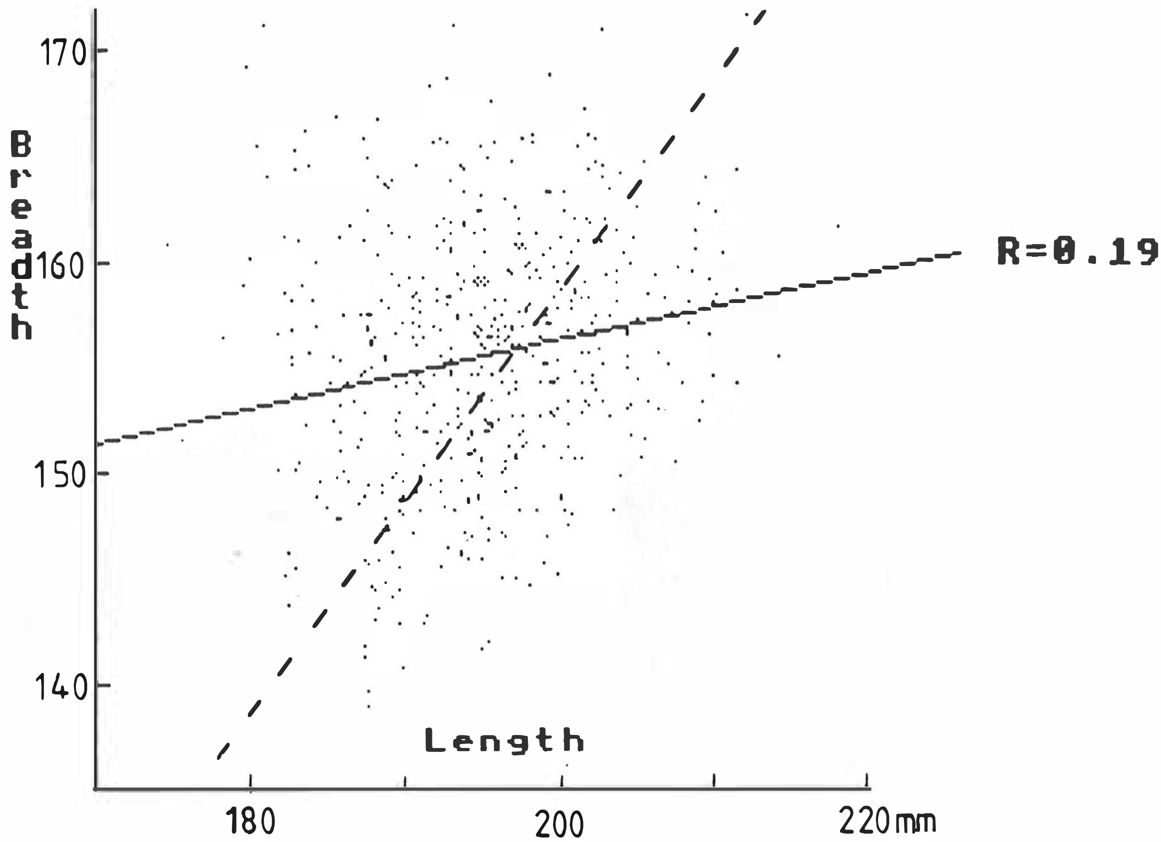


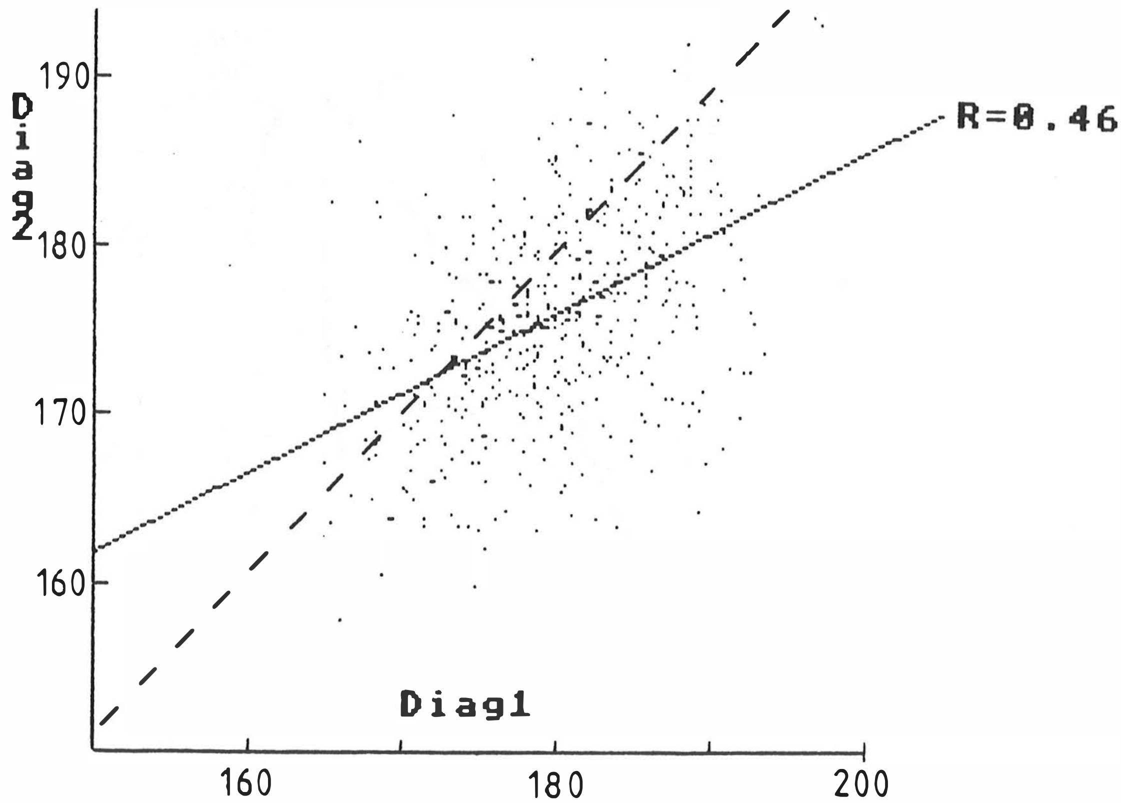
Circum/mm	y/mm
540	83
560	86
580	91
600	94
620	97

1. Side view of BS 6489 headform showing AA plane, and the boundary ACDEF that the helmet must cover.

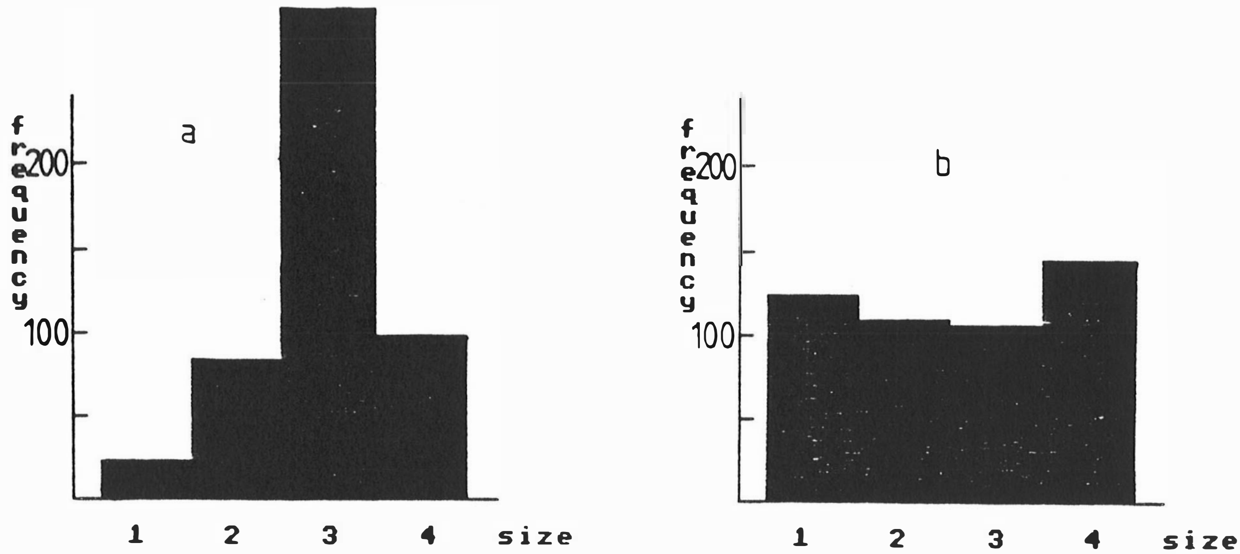


2. Horizontal section through a head 86mm below the vertex, showing transducer positions 1 to 8.

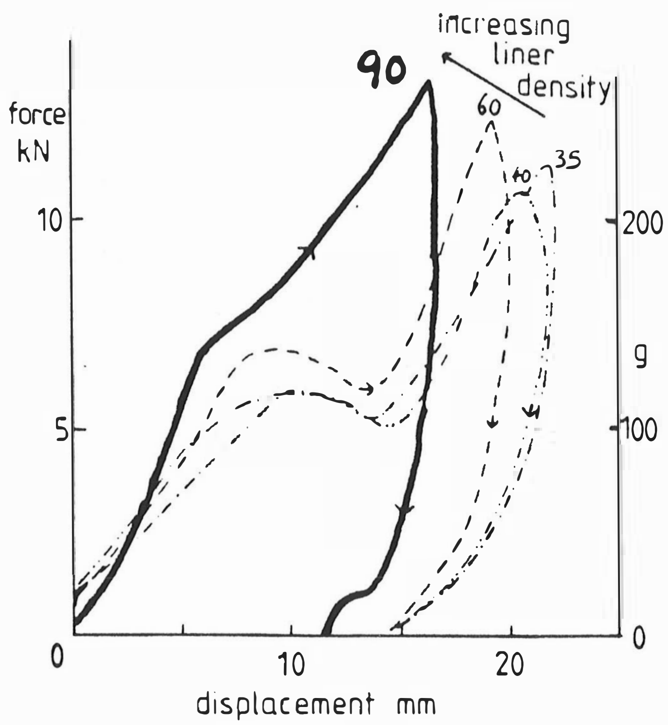




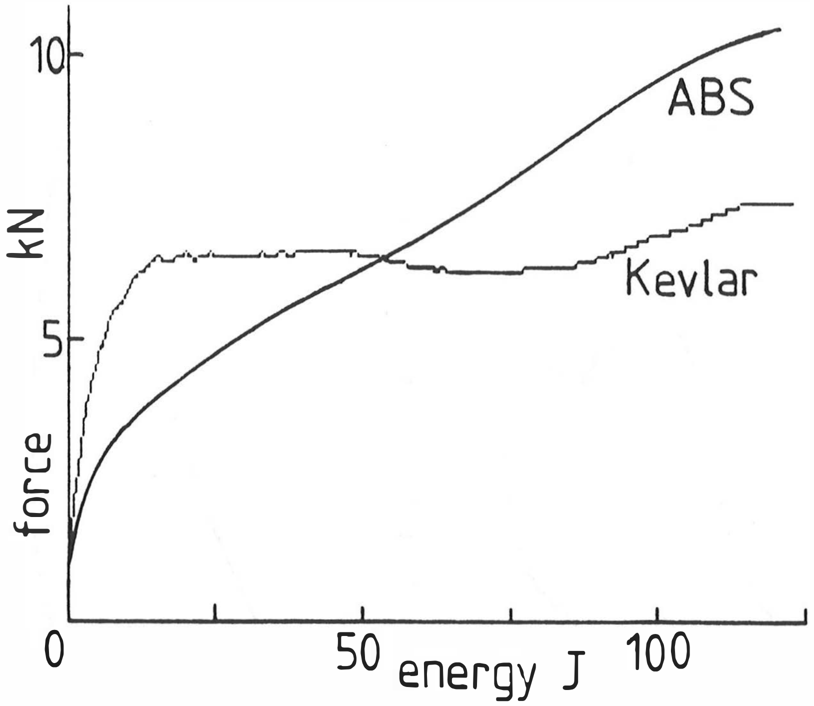
3. Cross plots of (a) head breadth versus length (b) head diagonals. Regression lines for —— heads and ------ headforms



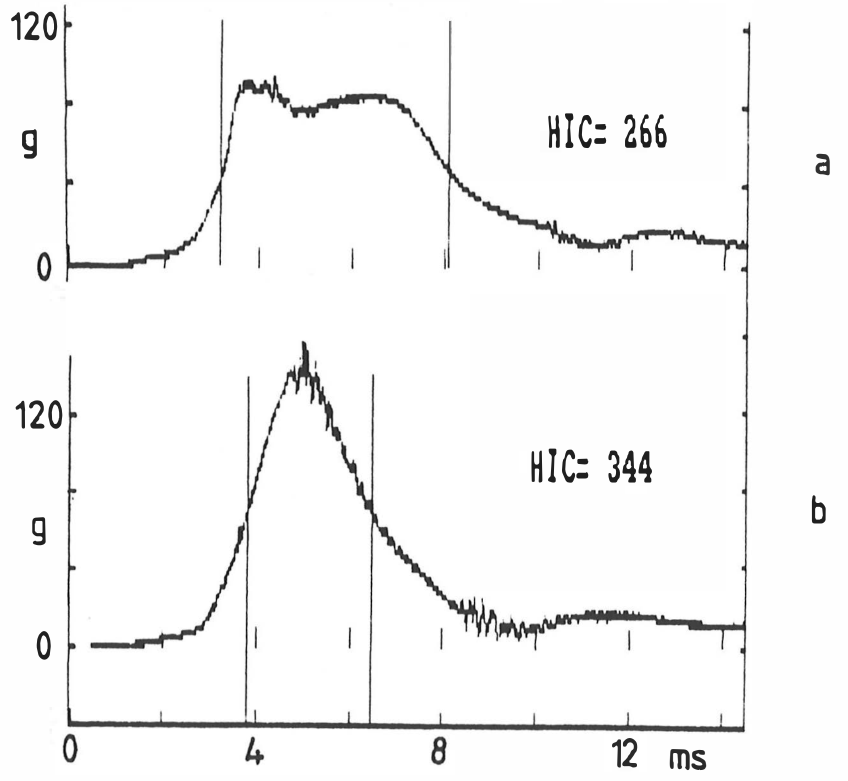
4. Helmet sizes needed by the 516 heads, choosing from (a) BSI sizes (b) survey sizes of table 3.



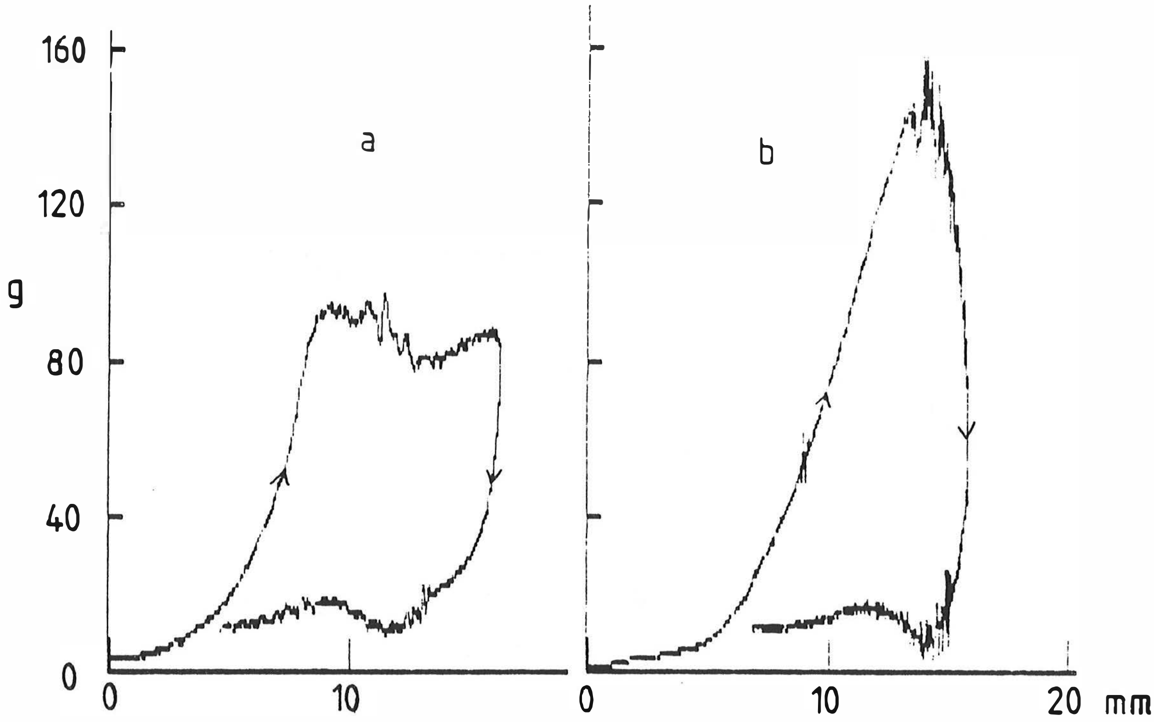
5. Force or head acceleration versus crushing displacement for impacts of a flat striker at 7m/s on an ABS helmet shell with different densities (Kg m^{-3}) of polystyrene foam liner.



6. Peak force versus impact energy input for helmets with different shell materials hit by a hemispherical striker at 7m/s.



7. Magnitude of the linear acceleration of the dummy head versus time for (a) a BS 2001 open face helmet hit on the side. (b) a BS6658 full face helmet hit on the back. Effective impact energy is 59J; the limits of the HIC integration are shown.



8. Linear acceleration versus compressive displacement of helmet, for the same helmets as in Fig. 7.