THE PROTECTION OF HORSE RIDERS IN IMPACTS WITH THE GROUND

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ABSTRACT

A variety of foams in equestrian helmets have been assessed and some found to be inadequate. The impact response of the helmet for side or frontal impact depends on the foam yield stress and thickness and the helmet curvature. Grass surfaces can absorb more energy in a fall than the helmet, however in falls onto tarmac roads it is predicted that high HIC values will occur for some helmet designs.

1. INTRODUCTION

Horse riding is considered one of the most dangerous sports, with 12 deaths among recreational riders in Britain in 1983. A survey of injuries in 1986 showed that of 1000 injuries 33% were head or facial injuries (1). In a number of these lateral blows occurred to the rider's helmet; 9 of these helmets were inspected in detail to estimate the degree of protection afforded (2). In this continuation of the research, the response of both the helmet and the ground surface was investigated, to see why in 8 of these cases the rider was concussed after a fall onto grass.

The design of riding helmets is greatly influenced by the national test standard. The current UK standards are BS 6473 : 1984 for horse and pony riders, and BS 4472 : 1988 for jockeys. The impact tests in these standards require tests at 2 and 4 points respectively (Fig. 1), the sites and impact energies being given in Table 1. The impact sites seem to be chosen more so that traditional designs can pass rather than from any epidemiology of impact sites. In contrast both the current French standard (3) and the U.S. Pony Club standard (4) require a much wider range of impact sites. The failure criterion in the U.K. Standards is that the force on the headform should not exceed 20 kN (equivalent to 300 g), and that the head acceleration should not exceed 300 g in the other standards.

TABLE 1. IMPACT CONDITIONS IN EQUESTRIAN STANDARDS

Standard	Headform type	Surface struck	Site	Position rel. to reference plane	Energy J
BS 6473 : 1964	fixed wooden	flat steel	front/rear	+ 13 mm + 30°	80
BS 4472 : 1988	fixed wooden	flat steel	front/rear side	+ 13 mm + 30° + 13 mm + 30°	110 80
US Pony Club	falling NOCSAE	flat steel + 12 mm rubber	front side/rear	+ 25 mm on	65 (for size 578 mm
French	falling ECE 22/02	flat steel	front side rear	+ 25° on + 30 mm	55 (for size 570 mm)

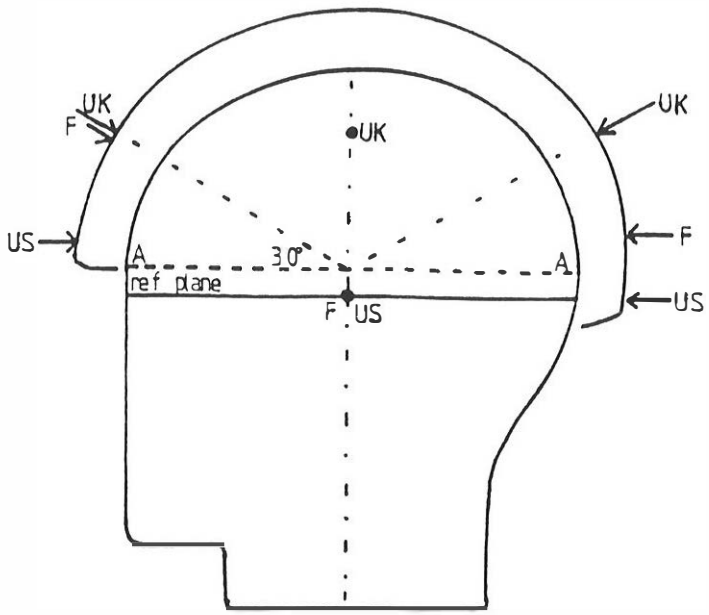

Fig. 1. Impact sites relative to headform and helmet, F-French, UK-BS4472, US-US Pony Club. Reference plane is 12.7 mm below AA' plane.

There is a disagreement between the views of certain Jockey Club representatives who are satisfied with current designs, as no jockey has died from head injuries in recent years, and those who compare the design of riding hats with the higher protection afforded by for example bicycle helmets. The recreational rider in the UK must often ride on public roads - a survey (5) showed that 25% of rides involved this. Therefore the protection from current helmet designs for falls onto road surfaces was of particular interest.

2. ANALYSIS OF HEAD, HELMET AND GROUND DEFORMATION

In the impact that occurs when a rider's head hits the ground there are three deformable bodies: the head, the helmet (if any), and the ground. It is useful to analyse the deformation mechanisms in all three to see which is providing the greatest degree of protection in the impact, and how the contact geometry changes as the force on the head increases.

i) the head or headform

For helmet testing there are two main designs of headform. One attempts to be rigid, with no shape change or energy absorption during the impact; the other attempts to mimic the deformation of the human head, without however fracturing. The solid magnesium alloy headforms of ECE Regulation 22/02 are an example of the former, and the NOCSAE headform for American football helmet testing an example of the latter.

Hodgson (6) compared the results of slow lateral compression tests of cadaver skulls with that of the NOCSAE headform. The latter has a silicone rubber 'skin' covering a hollow metal casting, and the measured lateral stiffness (force divided by ear-to-ear deflection) is 1.59 kN/mm. However McElvaney's (7) review quotes cadaver skull stiffnesses in the range 1.4 - 3.6 kN/mm for the anterior-posterior tests and 0.7 to 1.8 kN/mm for lateral tests. It is clear that the compliant skull absorbs a (variable) amount of energy on impact. The difficulty with using a compliant headform is that its impact stiffness must be carefully specified otherwise tests results from different test houses will not be comparable. At relatively low impact kinetic energies (50 J) and for high allowable forces on the headform (a 300 'g' failure level for a 5 kg headform represents a 15 kN force), a high compliance headform could pass the test without much of a helmet being present. Figure 2 shows the impact force versus headform deflection for the crown of a Med-Eng headform hitting a flat steel plate. These headforms ware made in Ottawa from polyurethane hard

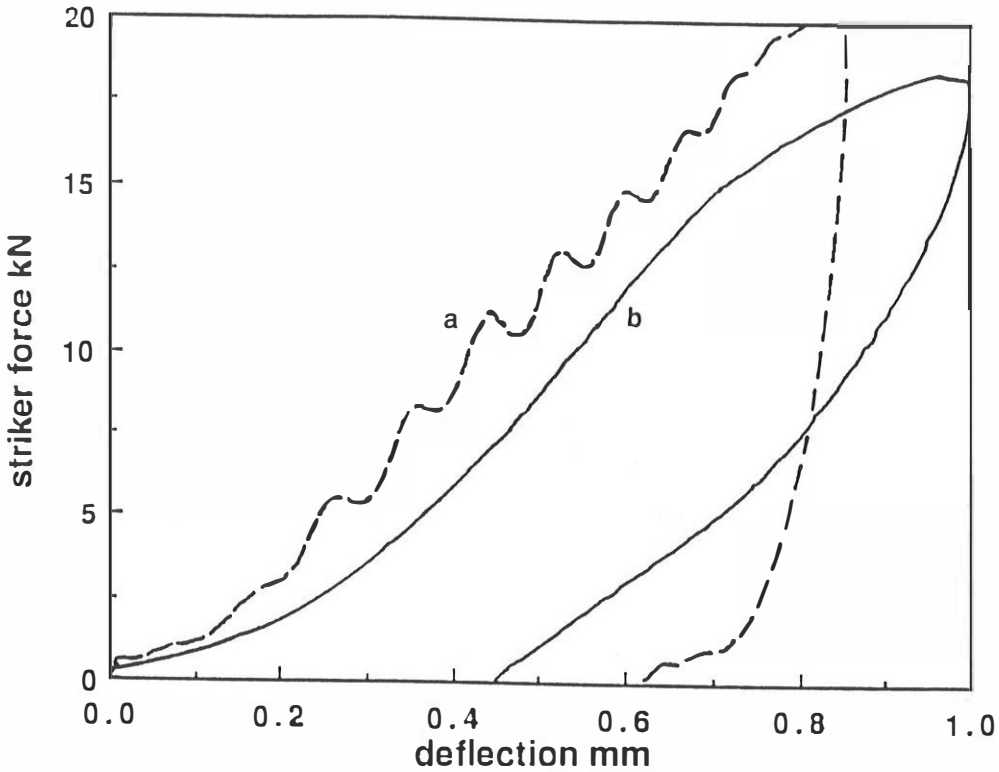

Fig. 2. Force - deflection relationship for a) Aluminium headform crown hitting tarmac road. b) Med-Eng polyurethane headform impacting its crown on a flat steel plate.

rubber filled with silica and are used by BSI for motorcycle and bicycle helmet testing. The slope k of the linear loading curve can be used to calculate the energy E absorbed or stored by the headform at a force level F, using

$$E = F^2/2k \quad \ldots\ldots\ldots\ldots \quad (1)$$

The slope k = 20 kN/mm in Figure 2 shows that only 5 J is absorbed by the headform when F = 15 kN. Other more compliant headform designs such as the NOCSAE headform could absorb a high percentage of the impact energy. The main reason for using a solid aluminium headform for testing is that it will absorb negligible energy, so the energy inputs calculated will be directly attributable to the helmet or the ground struck. Using a 'rigid' headform would be inappropriate if its failure to change shape in the impact radically changed the deformation pattern in the helmet. We conclude later that for survivable impacts, and for most impact sites/surfaces the errors in using a 'rigid' headform are not large.

ii) the helmet

Many designs of riding helmets contain the following four elements (Figure 3):

a) a hard outer shell made from a thermoplastic, or a thermoset reinforced with woven glass fibres (GRP).

b) a head band of cloth covered soft foam that provides a comfortable close fit to the head.

c) a suspension cradle of 4 webbing loops linked by a draw string, that provides an adjustable air gap at the top of the helmet.

d) an energy absorbing liner of hard foam or cork.

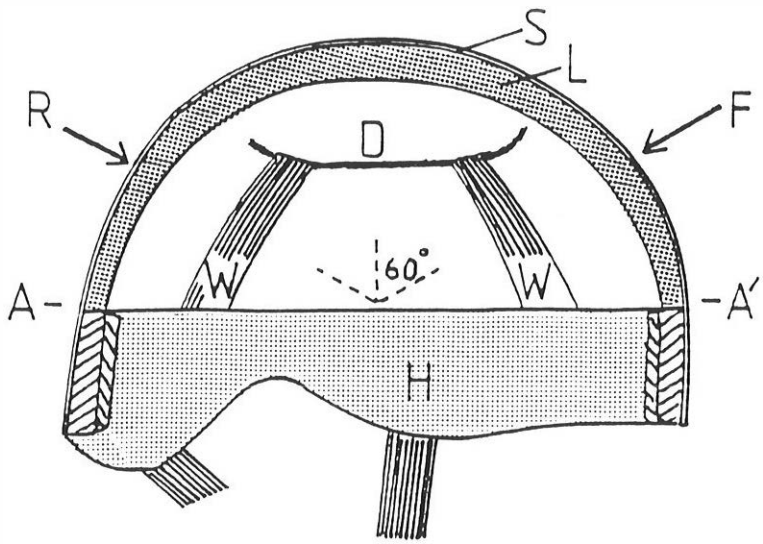

Fig. 3. Typical construction of a BS 4472 : 1966 jockey skull-cap. H headband, S shell, L liner, W webbing, D draw string.

In recent UK standards the helmets have been impact tested with the draw string unfastened, so that the suspension cradle does not function to absorb energy for blows near the top of the helmet. Consequently some helmets no longer contain suspension cradles and the liner d) may extend to the base of the shell. Because of the great variety of foam materials in equestrian helmets, we have measured the compressive stress-strain behaviour of these under impact conditions (Figure 4). The results can be divided into two categories.

i) the 'impact protection' foams have initial yield stresses in the range 0.5 to 1 MPa. They include traditional cork and rigid polyurethane foam, both of which have a much higher yield stress at 70% strain than initially, and high density polyethylene and polystyrene foam which have a nearly constant yield stress.

ii) the 'soft' foams have initial yield stresses less than 0.2 MPa. Only low density polyethylene foam of 40 kg/m^3 density is shown in Figure 4, but many headband 'comfort foams' of flexible polyurethane open-cell type also fall in this category.

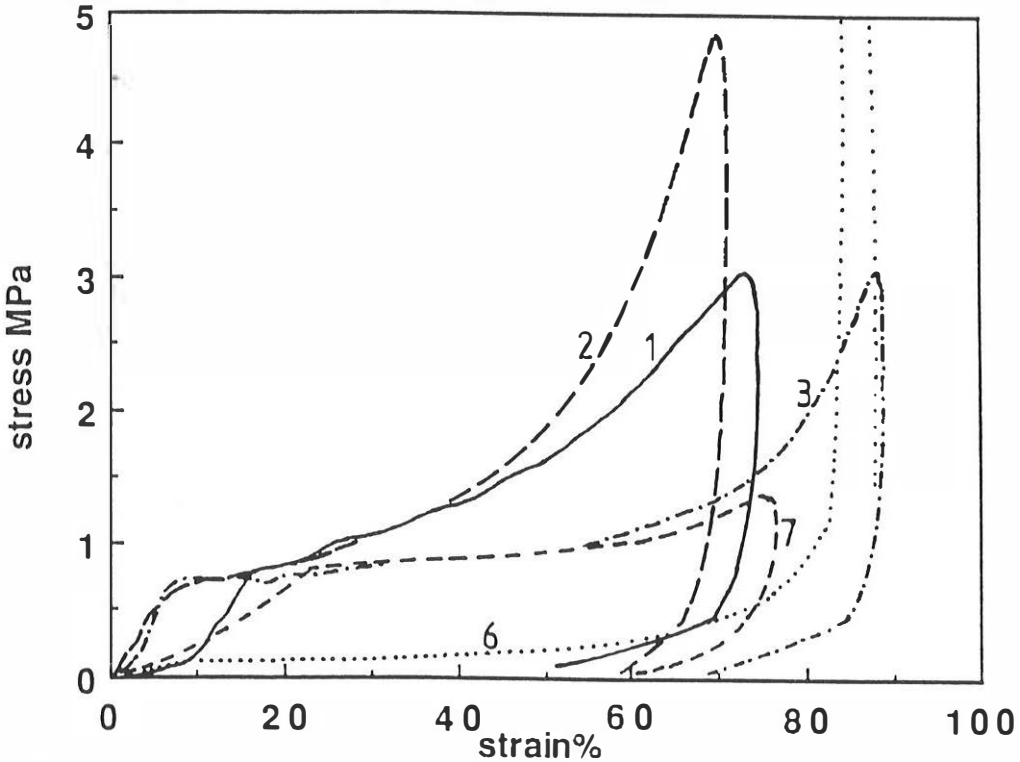

Fig. 4. Impact compressive stress-strain curves for foams from equestrian helmets. 1 cork (200), 2 PU (126), 3 PS (56), 6 LDPE (40), 7 LDPE (170).

In order to produce a figure of merit for the protective capacity of these foams we proposed (8) using the area under the stress strain curve up to a stress 2.5 MPa. This limiting stress is an approximation, reached by measuring the contact area for GRP shell riding helmets when a 200 'g' headform acceleration reading was measured in laboratory impact tests with a flat surface. Table 2 gives the energy density value of the foam material as a figure of merit. Although the theoretical maximum value is 2.5 J/cc for a material compressing 100% at a constant 2.5 MPa stress, the best 'impact protection' foams have values around 1 J/cc. In contrast the 'soft' foams have values of 0.35 or less. It should also be mentioned that some impact protection foams such as HDPE largely recover in about 1 day (8) and have an energy density in a second impact about 70% of the initial one, whereas other foams such as polystyrene are poor in a second impact.

TABLE 2. IMPACT DATA FOR FOAMS FROM RIDING AND OTHER HELMETS

No.	Source	Material	Thickness mm	Density kg/m^3	Energy density $\sigma < 2.5$ MPa J/cc
1.	BS 4472 at top	cork	10	200	0.75
2.	BS 6437 liner	polyurethane	varies	126	0.65
3.	BS 4472 liner	polystyrene	varies	56	0.81
4.	Military helmet	HDPE	13	98	1.06
5.	BS 4472 at top	LDPE	11	40	0.34
6.	BS 4472 headband	LDPE	9	40	0.23
7.	BS 4472 headband	LDPE	5	170	0.56

The foam densities are given because the yield stress increases approximately as the 1.5 th power of the density, so the density is carefully chosen to give suitable yield stresses.

There are two main mechanisms by which energy is absorbed in a helmet. Figure 5 shows these in relation to a lateral or frontal impact site. The first load path to the head is through the yielded foam that is below the contact area with the object impacted, and the second is via the elastically deformed shell to surrounding areas of un-crushed foam, and hence to the head. The shape, material and thickness of the shell at the impact point will determine the proportions of force transmitted or energy absorbed via the two routes. In some circumstances, such as a motorcycle helmet hit near the crown, the doubly convex shape of the shell of thickness about 4 mm means that it takes a high force in the region of 2 to 4 kN to buckle the shell inwards. It is then expected that the shell absorbs 30% to 40% of the impact energy (9). However here we are concerned with thinner shells and with impact sites that lie at the front or sides. In this case the rigid foam liner will be expected to absorb most of the energy, as the unconstrained lower edge of the shell allows it to deform easily.

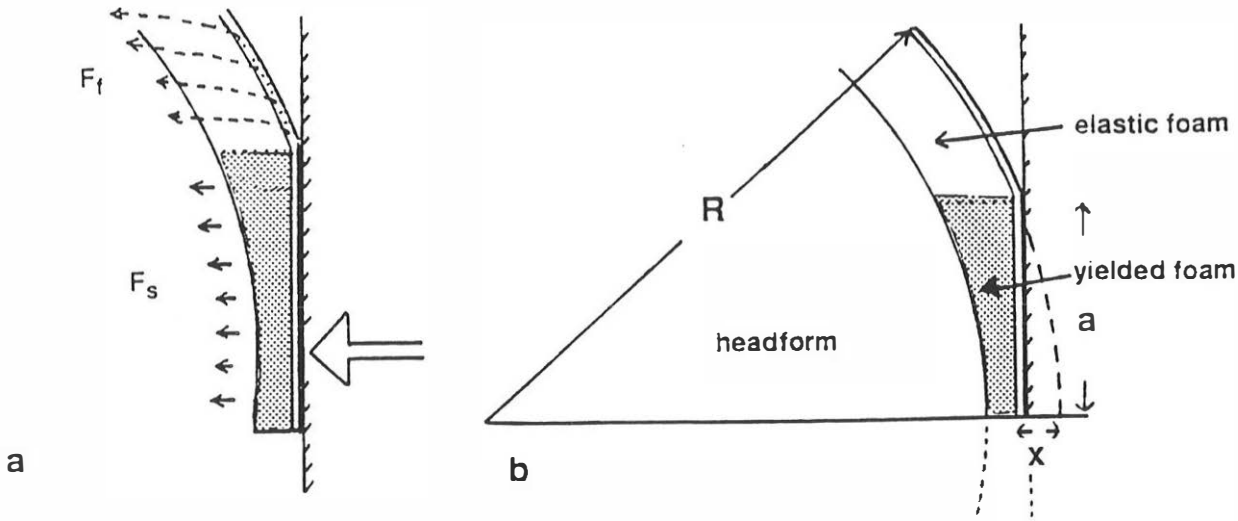

Fig. 5. The side or front of a helmet during impact with a flat surface a) force transmission to head b) contact geometry.

The energy absorption or storage mechanisms are

i) in the yield foam liner. The contact geometry beteen a flat impactor and the spherical outer surface of the foam liner is shown in Figure 5b. So long as the amount of liner crush x is much less than the radius of curvature R of the spherical outer surface then the contact area A is given by

$$A = 2\pi Rx \qquad \ldots\ldots\ldots\ldots \quad (2)$$

It is assumed that the foam yields over an area A, of radius a, and has a constant yield stress σ_y (in reality the yield stress will be highest in the centre of the contact area where the strains is highest). Consequently the force transmitted by the foam is

$$F_f = 2\pi R\, \sigma_y x \qquad \ldots\ldots\ldots\ldots \quad (3)$$

so long as the strain is increasing. Once the foam begins to unload the force drops rapidly as the cell walls do not fully recover from their buckled state. Substituting typical values of R = 160 mm, $\sigma_y = 0.7$ N/mm^2 for the side of a helmet liner into equation (3) gives an effective foam spring constant on loading of

$$K_f = F_f/x \approx 700 \text{ N/mm} \qquad \ldots\ldots\ldots\ldots \quad (4)$$

Nearly all this energy is absorbed by polystyrene foam; typically less than 5% is returned to the rebounding head.

ii) in the bent shell and elastic part of the foam liner. It is difficult to make a precise estimate of the force transmitted this way, but this will not matter if the value is much less than that in i) One approximate method is to perform slow compression tests of the complete helmet between two parallel plates without any headform being present. The difficulty is that the stress distribution in the shell differs from that in a side or front impact. However the values of the static loading stiffness K_S, given in Table 3, show that these are much smaller than either the foam crushing 'spring' constant K_f of the last section, or the stiffness of cadaver skulls measured in slow tests. The values is Table 3 should be doubled to

produce the stiffness between the contact point and the centre of the headform/helmet, to be comparable with the K_f values. After doing this they are less than 10% of a typical K_f value, and less than 3% of the mean lateral cadaver skull stiffness.

TABLE 3. COMPRESSIVE STIFFNESS OF RIDING HELMET SHELLS LOADED SLOWLY BETWEEN PARALLEL PLATES

Standard	Shell Construction	Thickness mm	Lateral Stiffness N/mm
6473	HDPE + short glass	2.5 - 3.1	16.4
4472	Woven glass rovings	1.9 - 3.2	32.5

iii) the ground. There is little published on the impact mechanics of turf or other riding surfaces, related to the impact of head shaped objects. The most relevant is work on safety surfaces for children's playgrounds (10). The usual test method is to drop a metal sphere of radius 82 mm containing a triaxial accelerometer, and to calculate the HIC from the resulting acceleration vs time trace. We however wish to know the force - distance relationship for the impact. The only information of this type was available for athletic running tracks, for foot shaped impacts (11).

The literature survey and theoretical analysis revealed the following approximate values for stiffness in N/mm

lateral cadaver skull (side)	700 - 1500*
filled polyurethane headform (crown)	20, 000
polystyrene liner (side)	700
helmet shell (side)	13 - 30*
packed cinder running track	3000
wooden running track	800

*Multiply values by 2 to be equivalent.

It was clear that further experimental investigations were needed.

3. RESULTS

i) Testing of helmets

Two series of tests were carried out' firstly in an attempt to reproduce the accident for the riding helmets recovered from accidents, and secondly some lateral impacts on recent designs of riding helmets. The test equipment (9) consists of a falling 5 kg flat striker, and a solid aluminium headform on a ball joint, mounted onto a quartz load cell. Usually the impact force on the striker is calculated from the acceleration of the striker, and the force transmitted through the headform is used as a check that force oscillations are not significant. The results are usually presented as striker force versus the deflection of the helmet (Figure 6). Often the initial stages of the behaviour can be approximated as a straight line; if so the slope of this line is given in Table 4. Secondly the area under the force - deflection graph up to a force of 10 kN is calculated. A 10 kN force causes a 200 'g' acceleration of a 5 kg head, an acceleration level that is likely to cause concussion. This area estimates the impact energy in Joules that would result in a maximum force of 10 kN, as lesser impacts at the same site will produce a the same force deflection graph while the deflection is increasing. Thirdly the helmet deflection at a 15 kN force (allowing for any initial soft foam compression) confirms that the liner foam is fully compressed at this high force level.

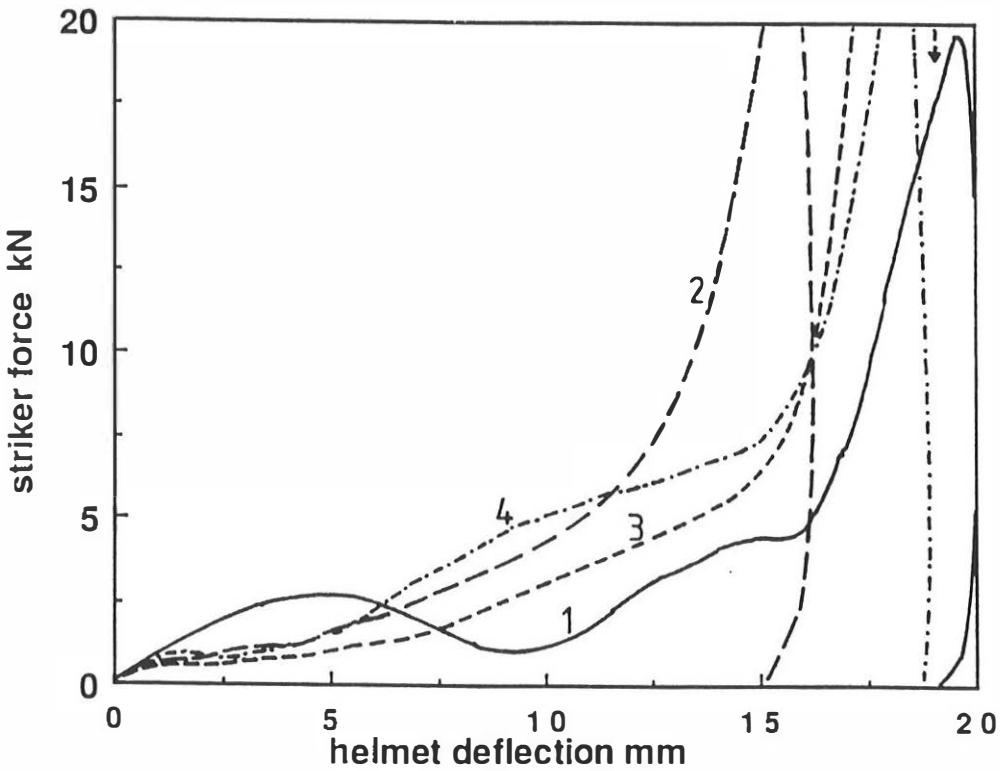

Fig. 6. Force versus helmet deflection for 95 J impacts on the side of riding helmets at AA plane with a flat striker. Nos refer to Table 4.

TABLE 4. IMPACT RESULTS ON BS 4472 RIDING HELMETS SIDE IMPACTS AT REFERENCE PLANE

No.	shell	Foam in headband	Foam 20 mm above headband	Deflection mm when F = 15 kN	Loading Stiffness N/mm	Energy when F = 10 kN	Input when F=15kN
1.	2mm GRP	6mm LDPE	10 mm PS	~ 18	non-linear	46	57
2.	1mm GRP	6mmLDPE	10 mm PS	12.0	540	39	51
3.	1.5mm GRP	6mm PS	11 mm PS	10.8	635	43	50
4.	3.5mm ABS	8mm PS	13 mm PS	14.8	595	63	74

The loading stiffness values are close to the theoretical predictions for polystyrene foam liners. Further experiments on bicycle helmets (12) show a wider range of values, with lower values when large ventilation channels are cut through the foam. None of the helmets could keep the force on the headform less than 20 kN for a 110 J impact, if the impact site was at the level of the reference plane at the side. Only the last helmet in Table 4 is manufactured to BS 4472 : 1988, the others are to BS 4472 : 1966 which has no lateral impact tests. If the helmet force-deflection response is taken to be linear and we require protection from a 110 J impact without the force exceeding 15 kN, then the foam liner must be thicker at the impact point : 20 mm of polystyrene foam and a loading stiffness of 550 N/mm would be suitable values.

ii) Testing of ground surfaces

A solid aluminum casting of a 560 mm circumference headform down to the 'reference plane' was fitted with an accelerometer that had its axis in the lateral or vertical direction. The headform could have been somewhat larger to represent the dimensions of a typical helmet shell, but this would produce results with the force scaled up by a small factor. The headform was released electromagnetically in free fall onto various ground surfaces from a series of heights up to 2.2 m.

Various types of response curve were found (Figure 7). Firstly it was seen whether falls from different heights (and hence at different impact velocities) followed the same force - deflection graphs. This occurred for turf but not for impacts into dry sand. If so the loading parts of the graphs were digitized at 1 kN intervals. When the graphs were nearly linear, loading stiffnesses could be calculated:-

grass on soft muddy ground	150 N/mm
packed earth (moist)	500 - 1000 N/mm
packed earth + small stores (dry)	1000 - 2000 N/mm
tarmac	18,000 - 26,000 N/mm

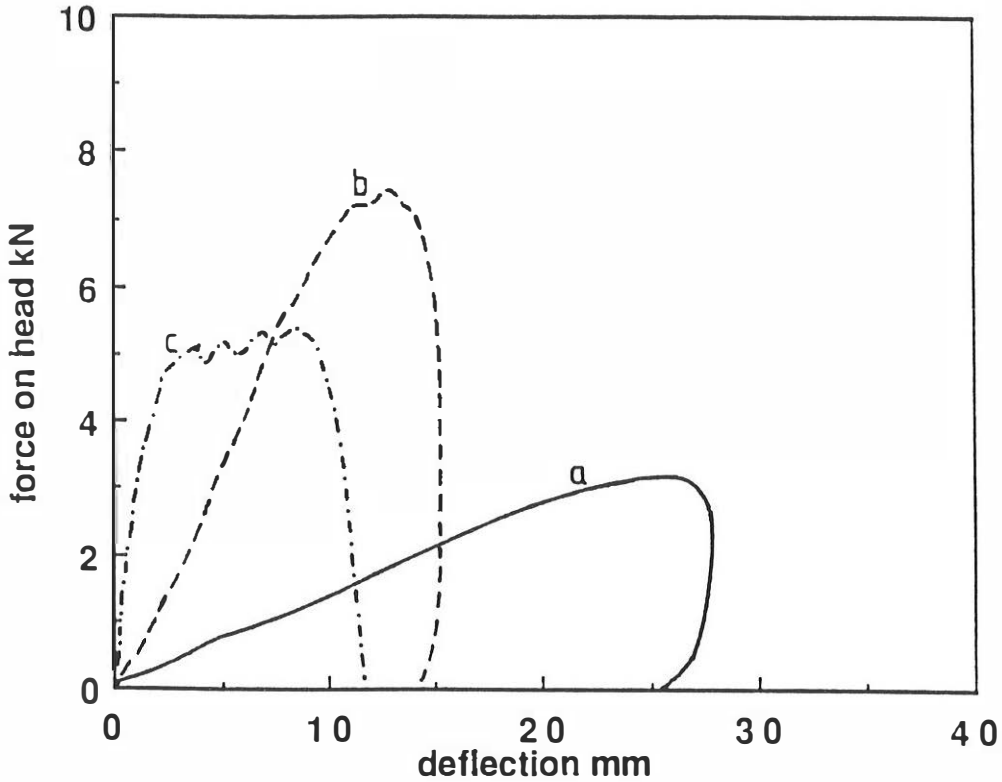

Fig. 7. Force versus deflection for impacts of aluminium headform crown with a) grass on soft ground 50 J, b) packed moist mud path 70 J, c) packed pebbles and dry earth 50 J.

iii) Predictions for falls onto ground surfaces

The assumption was made that when a rigid headform plus helmet hits the ground, at a particular contact force level it is possible to add the experimental deflections for a) the helmet hitting a flat steel plate, and b) a rigid headform or helmet shape hitting the ground. This ignores the fact that the shape of outside of the helmet when it hits the ground will be somewhere between that in a) and b), so that at a given force, the helmet deflection will be less than in a) and the ground deflection less than in b). Hence the predicted deflections will be overestimates and the energy absorption greater than in reality. Figure 8 shows some predicted helmet + ground responses and Table 5 gives the predicted results of falls from the riding height of 8 feet, with an impact energy of 120 J.

Table 5. PREDICTED PEAK FORCE (kN) TRANSMITTED TO THE SIDE OF THE HEAD FOR A 2.44 m FALL ONTO DIFFERENT GROUND SURFACES

Helmet of Table 4	Tarmac	Pebbles + dry earth	Packed moist path	Grass on soft ground
1	> 19	13.9	9.4	4.7
2	> 19	>19	10.0	5.2
3	> 19	>19	9.9	5.1
4	> 19	13.6	9.0	5.3

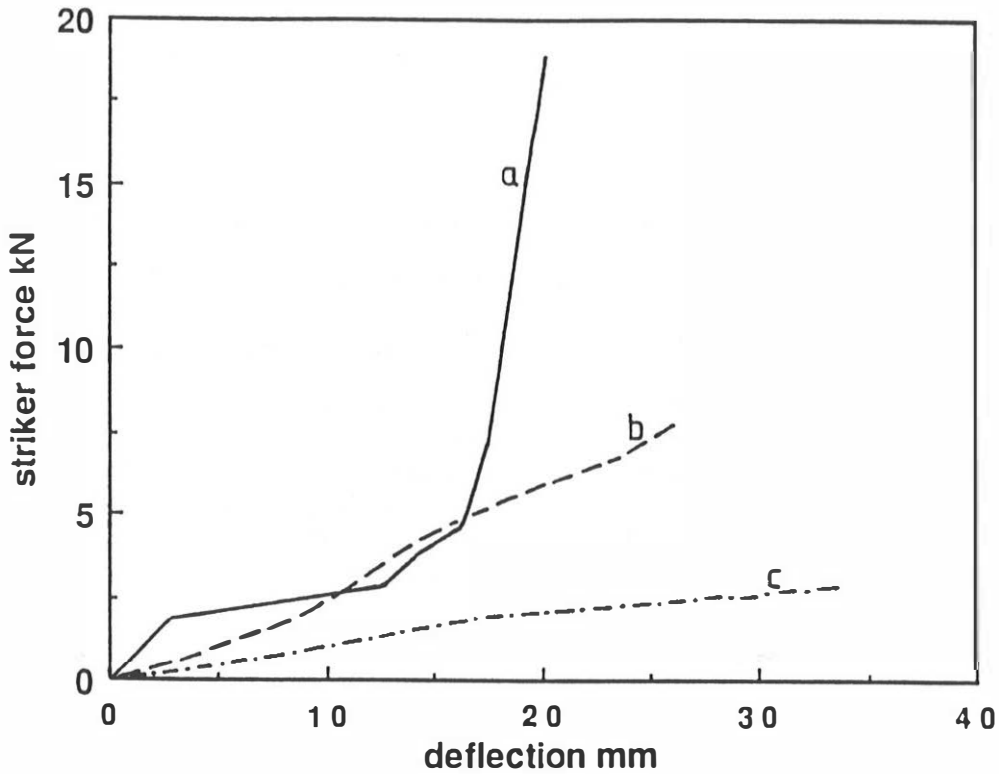

Fig. 8. Predicted force - deflection graphs for lateral impacts of a) helmet 1 of Table 4 on tarmac b) helmet 4 on packed moist path, c) helmet 1 on soft grass.

DISCUSSION

The results in Table 5, which are underestimates, show that existing riding helmets will not protect the side (or back or front) of the head from a vertical fall of 8 feet onto a tarmac road. On the other hand they would be adequate for a similar fall on a field or path. This probably explains why the competitive riders, whose helmets were examined in (2), were concussed when they fell on grass, whereas the one recreational rider who fall backwards onto a road was killed.

Considering the risks in riding there is no logical reason why the impact protection level is high at some sites, lower at others, and not tested at others. A vertical fall from 2.4 metres onto at hard surface would give a 110 J impact energy to the head, and the helmets should be tested at this level at any site above the reference plane. Even these tests would not produce a helmet that could protect a rider from a fall at speed.

Testing helmets between nearly rigid headforms and a rigid flat steel plate produces a loading curve that can be explained theoretically; the initial slope from the foam yield stress and the helmet radius of curvature, and the sharp rise above 15 kN when the deflection is equal to the foam thickness. The foam liners of equestrian helmets should not taper in thickness from the crown to the base of the helmet, because of the reduction in protective capacity. Following the theoretical analysis of equation (3) the foam should be of lower average yield stress at the sides of the helmet where the radius of curvature is larger, than at the front. One method of achieving this is to incorporated ventilation holes and channels in the foam at the side.

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