PROTECTION OF THE SIDE OF THE HEAD

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ABSTRACT Helmet testing has been carried out using a dummy with a flexible neck, to identify the events that occur in impacts occur to the side of the head. The levels of angular acceleration correlate with the peak linear accelerations; the peak values occur before the large angular motions of the head. For the better designs of helmet, tested at the side with an impact energy equivalent to 30 J in a rigid anvil test, neither value is considered to be injurious. The load spreading efficiency of the rigid foams used in soft shell bicycle helmets is good so long as the foam does not bottom-out at the impact site, and there is evidence that polypropylene foam is better at load spreading than polystyrene foam. We conclude that the side of the head can be protected by a suitable helmet design.

1 INTRODUCTION

The side of the skull is especially vulnerable to fracture[1]. In a review[2] of the force, on a steel striker having flat ends of approximately one inch diameter, necessary to cause depressed fractures in cadaver skulls, the average fracture load for parietal sites was quoted as 3.5 kN. In experiments where cadavers were dropped so that the sides of their heads struck a flat metal plate, skull fractures were observed when the maximum impact force exceeded 11 kN[3]; the contact area is larger and there are no stress concentrations at the edge of the indentor so the fracture force is larger. The force to cause a skull fracture depends on the impactor shape, but the high stiffness of the skull means that a small diameter metal striker can cause a skull fracture if it directly impacts the side of the skull with a moderate energy.

There has been debate in the UK whether it is possible to have rigid foam in the ear region of helmets, because of the risk that localised forces applied through the foam could cause basal skull fractures. Shanahan[4] showed that some lateral skull fractures in US Army helicopter passengers were caused by the design of rigid ABS earpieces, which could transmit a force in excess of 20 kN to the skull without fracturing. In the new design of helmet[5] there is a crushable ABS earpiece and there is protective polystyrene foam at the sides.

The only impact test in current standards that could apply a high localised pressure to the headform is the penetration test using a conical spike. This has been criticised since the frequency of accidents involving spikes is extremely small[6] and the test causes the outer shell of helmets to be excessively thick. Aldman[7] proposed the replacement of the penetration test by an impact with a 50 mm diameter hemispherical striker. He stated that a depressed skull fracture would be likely in the temporal area, if the impacted area was less than 5 cm^2 and the localised pressure exceeded 4 MPa. The small diameter striker test is less severe than the penetration test for soft shell cycle helmets [8]. In the proposed test[8] the force, measured with a load cell of surface area 110 mm^2 imbedded in the headform, must not exceed 2 kN(a pressure of 18 MPa) when the helmetted headform falls 700mm onto a rigid 50 mm diameter hemispherical anvil. The impact energy, ignoring the mass of the helmet, is 35 J.

There is concern that angular acceleration of the head is the main cause of diffuse neuronal damage in the brain. Research on monkeys showed that the direction of rotational acceleration is important, with coronal head motions(side to side acceleration) producing the most serious neurological disturbances[9]. Current helmet test standards do not include rotational acceleration tests because :-

(a) if there is a direct blow on the helmet, there is always linear acceleration as well as rotational acceleration, and measures to reduce the linear acceleration also reduce the rotational acceleration.

(b) there is little that can be done to reduce the rotational acceleration. The smooth outer shell of motorcycle helmets will slide on a road surface without undue 'friction'; measurements of the tangential forces in oblique impacts in the BS 6658[10] motorcycle helmet tests have shown that the majority of thermoplastic and fibreglass reinforced shells have similar tangential forces, and that the main influence on the peak force is the radius of curvature of the impact site.

(c) rotational acceleration tests are expensive to carry out, and there is no generally accepted test rig for such a test.

All current or obsolete helmet test standards use an isolated head, with no torso. The headform may be:

1 immovable, as in some equestrian helmet standards (BS 4472)
2 able to move along one linear axis only, having a rigid neck attached to a guidance rail or wires, as in the current UK motorcycle helmet standard BS 6658.
3 allowed to move in an arc on a swing arm of length about 1 metre, as in the pre-1985 UK motorcycle helmet standard BS 2495.
4 free, as in the current Regulation 22 motorcycle helmet standard[11]

The mounting of the headform has consequences on the angular acceleration of the head. In cases 1 and 2 there is zero angular acceleration, in case 3 the angular acceleration is very small, whereas in case 4 there will only be an angular acceleration if the head hits an oblique anvil.

In the research we wished to assess the magnitude of angular acceleration associated with linear acceleration, when there is a lateral blow to the head. We also wished to assess the efficiency of different helmet constructions in preventing high localised skull forces in the temple region.

2 CONSTRUCTION OF INSTRUMENTED DUMMY

2.1 Modification of the Ogle dummy

The OPAT dummy from Ogle Design Ltd, Letchworth is intended for use in car crashes. Its neck is a cylinder of solid rubber of diameter 76.5 mm, height 110 mm and hardness IHRD = 57, which corresponds to a shear modulus of 0.9 MPa. The cast aluminium skull is covered with a layer of plasticised PVC which is 5 to 10 mm thick, and has a hardness of IHRD = 55, which corresponds to a shear modulus of 0.8 MPa. The thickness of the PVC skin is 5 ± 1 mm in the lateral impact site used. This material is heavily damped, being close to its glass transition temperature, and the coefficient of restitution measured by bouncing a steel ball bearing from it is only 0.12.

The drawbacks of the OPAT dummy are its very stiff neck, the propensity of the thin aluminium headform to ring at about 1 kHz when it is struck, and the shoulders being a fixed distance apart and unable to twist. We reduced the ringing of Al skull casting by fixing a large number of 25 mm square by 1 mm thick Aluminium plates to the interior with a high loss polyurethane rubber. The shear of the polyurethane between aluminium layers causes high losses when the skull is deformed. The exterior PVC skin was glued in place with a polyurethane adhesive. The mass of the head and instrumentation inside it was 4.20 kg. We measurement of the angular inertia of the modified head, using a torsion pendulum, as 0.021 kg m^2 about the x axis (nose to rear of head) and 0.025 kg m^2 about the y axis (ear to ear). These values compare with the inertia values of the 50th percentile human head (mass 4.4 kg) of $I_x = 0.022$ kg m^2 and $I_y = 0.023$ kg m^2 [12]. In the test program the headform rotates about the x axis.

The new neck is flexible for both fore-and-aft and the side to side bending(Figure 1). It is a modification of a neck with fore-and-aft flexibility [13] developed for car passenger whiplash testing. It has much lower bending stiffness than the necks of the OPAT or Hybrid III car crash dummies, since it uses pin joints to allow the rotation which is restrained by the compression of polymer foam. Foam has the advantage over solid rubber in that it can compress to less than 10% of its original thickness without bulging sidewards, whereas the thin layers of rubber bonded to metal plates in the Hybrid III neck have very high Youngs moduli because of the high shape factor of the rubber blocks. The shaped blocks are aluminium rather than Acetal plastic used in the Swedish neck, and the foam used is a low density polyethylene foam of density 70 kg m^{-3} from Zotefoams Ltd. The blocks allow the neck to move by 50^o in either lateral direction or backwards, whereas it can move by 80^o forwards. The hardened steel 3 mm diameter pins are ejector pins from injection moulds. The foam returns about 40% of the energy used to compress it, so the motion of the neck is heavily damped.

The dummy should be positioned in a standing position for the impact tests but it was unable to fall realistically to the ground, and its shoulders cannot twist or move relative to the rigid lumbar spine. In the tests the dummy was laid with its back resting on a 120 mm thick polyurethane foam cushion on a table, while the head and neck are unsupported(Fig. 2). The cushion allows up to 50 mm of vertical movement of the torso after the impact from the vertically falling striker of a helmet test rig. Rubber bands connect the chin of the headform to the ribs, to prevent the head slumping prior to testing.

2.2 Transducers in the headform

The instrumentation at the centre of gravity of the OPAT headform. The outputs of the x, y and z channels of the Kistler model 8694 piezoelectric triaxial accelerometer are combined as vector components, and the magnitude of the total linear acceleration is calculated. The acceleration signals are recorded digitally without filtering, but then digital filtering is applied using a Hanning filter with a cutoff frequency of 2000 Hz. This has a sharper rolloff rate at 18 dB per octave than passive filters

The magnetohydrodynamic angular velocity transducer is a Model ARS-01 from Applied Technology Associates of Albuquerque. This has an angular velocity sensitivity of 0.0677 V/(rad/s) and bandwidth of 0.3 to 1000 Hz within 3 dB. This means that very high frequency angular velocity changes are effectively filtered out of the recorded signal, and also that it is not possible to carry out a quasi-static calibration of the angular velocity transducer. The output signal is digitised with an 8 bit A/D converter and the noise level is typically ±1 bit. The angular velocity changes almost monotonically, at typically 1 bit per 10 time steps. If the angular acceleration is calculated by dividing the change in angular velocity by the time step, the result is very noisy. Hence the angular acceleration $\ddot{\theta}$ was only calculated when the digital angular velocity signal $\dot{\theta}$ changed by more than 2 units, using

$$\ddot{\theta} = \frac{\dot{\theta}_{i+n} - \dot{\theta}_i}{n\,\Delta t} \qquad (1)$$

2.3 Transducers on the torso and striker

Pressure sensitive film (Super low pressure Prescale film, from the Fuji photo Co Ltd, Tokyo), was placed on the surface of the headform below the impact site. We had previously[14] used this material to measure the load distribution in impacts on helmets. It has a range of sensitivity from 0.1 to 5 MPa. A Kistler linear accelerometer (Piezetron model 8604, range 5000 g) was mounted on the rear face of the striker (of mass 5 kg), and a Endevco 2220 C miniature linear acceleration transducer mounted on the 'sternum' of the dummy chest to measure the torso movement.

2.4 Calibration of the neck stiffness

Figure 3 shows the force versus lateral deflection **y** of the midpoint of the head, which is a distance of 232 mm above the base of the neck. There is some hysteresis on unloading, but the slope of the nearly linear graph can be described by

$$y = 7.6\,M \qquad (2)$$

where M is the applied bending moment (the applied static force times 0.223 m). The graph is linear until the deflection reaches 80 mm, when the limit of rotation of the neck vertebrae is approached. Assuming that the head moves along a circular arc, equation (2) means that the angular stiffness of the neck is 0.53 Nm / degree. The angular stiffness of the Swedish[12] rear impact neck is not given directly, but using their results that a torque of 30 Nm is needed for an 80 degree movement, its stiffness is 0.4 Nm / degree. The angular stiffness of the laminated rubber Hybrid III neck is ten times higher at 4 to 5 Nm / degree[15]. Repeated impacts on our neck show that the response of the foam is constant for at least 10 impacts.

3 EXPERIMENTAL RESULTS

3.1 Helmets tested

Helmets of two types were tested(Table 1). These were soft shell bicycle helmets with two types of polymer foam, and a variety of hard shell helmets. The polypropylene cycle helmets were designed to be used with a thin thermoformed plastic covering, but they were supplied to us without this microshell. The polystyrene cycle helmet is intended to be used with a stretch-cloth cover, but this was not used. The thickness of rigid foam should be constant over the protected area of the head, but in several cases it is extremely variable. The fireman's helmet has an industrial hard-hat suspension system in the crown so the foam is thin in the crown. In the Jockey skull cap the rigid foam end above the headband which is made of LDPE foam covered with a layer of very soft open cell foam. In the 1994 design riding hat the polystyrene foam does extend to the base of the hat, but it is thinned there to allow the insertion of a soft foam strip. The area of the head covered by the helmets varies, with the riding and cycle helmets not covering the dummy ear.

Table 1 Construction of the helmets tested

No	shell material	shell thickness mm	helmet type	liner foam	liner thickness at side mm	liner density kg m^{-3}	helmet mass kg
1	none	-	cycle	polystyrene	20 - 30	50	0.29
2	none	-	cycle	polypropylene	24	70	0.2
3	ABS	5.0	motorcycle	polystyrene	25	55	1.33
4	GRP	1.5	firemans	polyurethane	15 - 28	90	0.82
5	GRP	1.5	Jockey cap	LDPE headband	6	40	0.44
				polystyrene above	15	53	
6	ABS	2.2	riding hat	polystyrene	14	63	0.49

3.2 Impacts with a flat striker

The impact site is centred on the AA line on the headform[10], so it is just above the ear on the OPAT dummy. As the dummy had a particularly stiff PVC ear, this was removed prior to the test programme. The observed impact events were as follows:-

a) There is a partially-elastic collision between the striker and the headform which lasts about 5 ms. This involves a large impact force on the striker F_S and a large linear acceleration of the headform. If the resultant linear acceleration of the headform is multiplied by the mass of the head(4.20 kg, ignoring the 0.26 kg neck) to give the impact force on the head F_H it is found that this is equal to 90% of F_S , with a correlation coefficient of 0.93 (*figure 4*). The implications of this are that the mass of the torso has no influence on the magnitude of the initial impact force. The bending stiffness of the neck is so low that the torso is not accelerated at all in the initial collision. The angular kinetic energy of the head must be a small fraction of the linear kinetic energy. The mass of the helmet has no influence on the forces, in contrast with our analysis[16] of impacts near the top of motorcycle helmets, which showed that the 1 kg helmet mass causes large oscillations of (F_S - F_H).
The motion of the torso, found by double integration of the acceleration of the torso during the initial impact, is negligible compared with the motion of the head. The torso moves slowly downwards over a period of 100 ms, reaching a maximum distance of 20 mm

b) The headform moves on the neck, on a time scale of 40 to 60 ms. The head moves with nearly constant angular velocity until the neck approaches its motion limit (fig 5 a) when the head decelerates. The striker is still falling and it catches up with the head again causing a second minor impact

c) The helmet can rotate relative to the headform, especially if it is limited in coverage at the side, so that the striker catches the lower edge of the shell.

Table 2 shows the results of the tests, compared with some lower energy impacts on the unprotected headform. All the helmets reduce the peak angular and linear accelerations to some degree. The degree of reduction of linear acceleration (a maximum headform force of 4.2 kN corresponds to a maximum linear acceleration of 100 g) is very similar for all the helmets containing rigid foam at the impact site, but is larger for the Jockey skull cap with the LDPE foam headband beneath the impact site. This is a result of the foams having similar compressive yield stresses and none of them having bottomed out in this test.

Table 2 Lateral impacts with a flat striker

No	helmet type	Maximum head force kN	Maximum striker force kN	Maximum rotational accel 1000 rad s^{-2}	Maximum rotation degrees	Impact energy J
1	PS cycle	4.82	4.88	11.3	48.8	90
2	PP cycle	4.86	4.89	10.1	48.5	90
3	motorcycle	4.38	5.56	6.3	40.1	90
4	firemans	5.79	6.21	18.9	41.7	90
5	Jockey cap	8.1	-	27.7	46.7	90
6	riding hat	7.73	4.02	35.3	47.1	90
	none	31.2	18.2	164		50
		40.7	17.4	227		

3.3 Impacts with a hemispherical striker

Williams[8] found the ranking of helmets by drop height to produce a 2kN localised force differed for 20 and 50 mm diameter hemispherical strikers. We used a 35 mm diameter hemispherical striker because it was available. The foam of soft shell helmets is indented by the striker; the striker keys into the helmet and no rotation of the helmet relative to the striker is possible. In contrast the striker can slip across the surface of a stiff and slippery thermoplastic helmet shell. Figure 5b shows the angular motion of a full face motorcycle helmet when struck at the side with the hemispherical striker. The initial linear acceleration is somewhat less than for the corresponding flat impact, but the peak is longer. This is the result of the contact stiffness being less great for a hemispherical striker, so the shell deforms more and softens the initial impact. For some of the helmets (the riding helmets and the polystyrene cycle helmet that is thin at the sides) the foam bottoms out and then the forces and pressures rise rapidly. By Aldman's criterion[7] there should be a depressed skull fracture for the helmets 1,5 and 6(Table 3). In general the maximum forces are less as the hemispherical striker penetrates the foam (and bends the helmet shell) quite easily. The total angular motion of the head is nearly the same as for the flat striker experiments as the impulse on the head is the same.

Table 3 90 Joule Lateral impacts with a 35 mm diameter striker

No	helmet type	Maximum head force kN	Maximum striker force kN	Maximum rotational accel 1000 rad s^{-2}	Maximum rotation degrees	contact area mm^2 (pressure MPa)
1	PS cycle	5.49	-	23.9	44.0	450 then 210(5)
2	PP cycle	2.79	2.82	6.3	46.5	960 (2)
3	motorcycle	3.27	-	10.8	34.4	-
4	firemans	3.2	3.85	15.1	42.4	
5	Jockey cap	10.2	11.76	47.9	43.6	520 then 240 (5)
6	riding hat	4.96	5.25	7.6, 30.2*	43.6	400(5)

* 2nd impact after helmet moved

Figure 6 shows the correlation between the peak linear acceleration and peak angular acceleration of the headform, for both flat and hemispherical striker impacts. The correlation coefficient $r = 0.69$ shows that the two variables are not strongly related. If there is a relationship between the variables, the best estimate of it is that the angular acceleration in rad s^{-2} is 15 times the maximum head acceleration in m s^{-2}.

3.4 Load spreading for impacts with the hemispherical striker

For the flat striker the radius of curvature of the striker is much larger than the thickness of the foam and there is uniform compressive strain through the thickness of the crushed area[14]. However the radius of the hemipherical striker is approximately equal to the thickness of the foam, so the strain distribution is non-uniform. Figure 7 shows that there is tearing around the edge of the crushed area in the polystyrene foam. Similar deformation occurs when polystyrene foam is compressed using flat faced indentors of small diameter[17]. When the blow is of sufficient energy for the PS foam to bottom out there is a contact patch noticeable on the inner surface of the liner. Polystyrene foam has a particularly low value of fracture toughness[18] which explains the easy crack propagation due to the tensile stresses at the side of the indentor.

With the PP foam there is far better recovery after the impact (Fig.7), and less tearing at the edges of the impact area, because the fracture toughness of the PP foam is higher than that of PS foam. In order to evaluate the load spreading ability of the two foams for the 35 mm diameter striker, some impacts were made with 25 mm thick flat sheets of foam supported on a flat rigid anvil. The maximum compressive strain in the foam was calculated for the centre of the contact patch, and the maximum cross sectional area of the striker calculated as 962 mm^2. The force on the hemispherical striker was divided by that for a block of foam of area 962 mm^2 undergoing uniform compression to the same strain. Figure 8 shows that the result for polystyrene foam is close to unity, whereas that for polypropylene foam rises to about 1.4. This means that with PP foam the striker force is spread over an area greater than the striker cross sectional area, but not for PS foam. Hence the pressure on the inner surface of the PP soft shell helmet is lower that on the outer surface.

The Fuji film experiments show that there are high localised pressures if either

a the liner of a soft shell helmet bottoms out
b a hard shell helmet contains a soft foam liner or an insufficient thickness of rigid foam.
c the helmet rotated on the headform between the first and the second impact so that the striker hit the unprotected headform on the second impact.

Figure 9 shows the Fuji film from the polystyrene cycle helmet; there is a double area of high pressure for the first impact, then the helmet rebounded and the headform rotated, so the next impact was a direct one on the skin of the headform. The contact areas are listed in table 3. For pressure calibration Fuji film was placed beneath rectangular blocks of foam, that were impacted between flat anvils and the maximum compressive stress in the foam was computed. The calibration set was examined with a Leica 500+ image analyser and the redness levels used to interpret the contact patches on the Fuji film samples from helmet impacts.

3.5 The equivalent impact energy in a fixed striker or fixed headform test

We wish to estimate the impact energy in a fixed striker test(BS 6658 or UN Regulation 22) or fixed headform test (equestrian helmet standard) equivalent to the 90 J flexible-neck + dummy tests. One method of finding the equivalent is to carry out a fixed headform test, and to vary the impact energy until the maximum headform force is the same as in the flexible neck test. This was done with the no-shell bicycle helmets, for which there is no contribution of the shell mass to the striker force, and for which the striker force is equal to the force on the headform. The fixed aluminium headform was tilted until the impact site was at the side; the instrumented striker was the same as in the tests with the Ogle dummy.

Polystyrene foam has a zero-strain rate dependence of the compressive yield stress, so there is a mastercurve along which all the force vs liner deflection curves proceed[19], whereas for polypropylene foam there is a slight strain rate contribution to the yield stress. Hence for fixed headform impacts the striker force can be plotted against the foam deformation distance, (fig 10) and the area under this curve is the energy input to the foam. Points on this curve will be good predictions of the maximum striker force for impacts causing lower foam deformations. The curve rises rapidly for energies exceeding 30 J because the strain in the centre of the contact patch has exceeded 90% so the foam is effectively solid. Table 4 shows the calculated fixed headform impact energies that will give the peak headform forces observed in the Ogle dummy tests. The maximum deflections can be compared with the foam thicknesses which are 25 and 24 mm for the PS and PP helmets respectively at the impact site. The maximum deflections for the flat striker are ony 50% of the foam thicknesses showing that the helmet could protect for a higher energy impact. For the hemispherical striker the foam deflection is approximately equal to the foam thickness showing that the foam has bottomed out.

Table 4 Fixed headform tests with no-shell bicycle helmets

Foam	Flat striker			Hemispherical striker		
	Max force kN	Impact energy J	max deflection mm	Max force kN	Impact energy J	max deflection mm
PS	4.88	31	12.2	5.49	34	25.6
PP	4.89	27	12.6	2.82	28	21.7

There are two reasons why the equivalent fixed headform impact energy is low. One is the momentum transfer from the striker to the headform in the flexible neck test. In the headform swingaway impact test in the obselete motorcycle helmet standard BS 2295:1977 the striker has initial velocity V_1 whereas the initial velocity of the headform and helmet is $V_2 = 0$. The analysis behind that standard ignores the mass of the swingaway arm and assumes that the headform moves in a straight line after the impact. Momentum is conserved in the collision, so the common velocity V_f of the masses at the moment of nearest approach is

$$V_f = \frac{m_1 V_1 + m_2 V_2}{m_1 + m_2} \qquad (3)$$

where the striker mass is m_1 and the headform plus helmet mass is m_2. We define the 'effective impact energy' $E_e \equiv$ energy input to the helmet up until the time when m_1 and m_2 have a common velocity. Irrespective of the coefficient of restitution of the helmet in the impact

$$E_e = \left(\frac{m_2}{m_1 + m_2}\right)\frac{m_1 V_1^2}{2} \qquad (4)$$

For a 4.5 kg striker falling onto a 4.6 kg headform plus helmet, the effective impact energy on the foam is 50% of the striker kinetic energy.

The second source of energy loss in the tests with the Ogle dummy headform is in the plasticised PVC scalp of the headform. The percentage of the impact energy dissipated in the PVC will depend on the striker geometry, the helmet design and the impact energy. However for the impacts considered here approximately 15 J of energy is used in the viscoelastic deformation of the PVC scalp.

Overall the 90 J striker kinetic energy in the flexible neck test is equivalent to a 30 J impact in a fixed headform or fixed anvil test. This shows that the impact energies in helmet standards is an underestimate of the head kinetic energy that is survivable in a real crash or impact. The exact equivalent will depend on the mass of the object struck, its shape and rigidity, and its velocity at the time of the impact. The 30 J fixed striker equivalent of the tests carried out here is lower than the approximately 50 J impact energy in current cycle helmet standards, and 150 to 180 J in motorcycle helmet tests. However the impact sites we used are lower than that specified in the cycle or riding helmet standards, which means that it cannot be assumed that existing products will 'pass' our tests.

4 DISCUSSION

The use of more realistic impact test conditions than those in national helmet standards has shown that there are phenomena that do not occur in the latter. In particular there is the movement of the impact point across the surface of the helmet, if there is a helmet shell. This causes additional volumes of foam to be crushed, and means that the total crushing distance of the foam can be considerably greater than the thickness of the foam liner. Note that in our experiments the impact direction is initially perpendicular to the helmet shell. It is difficult to conceive an accident where the victim's head does not rotate as a result of an impact. Even a blow on the crown of the head is likely to lead to head rotation when the spine bends(buckles). Hence perpendicular impacts onto rigid hemispherical anvils, using the non-rotating headforms of most test standards, are likely to concentrate the foam crushing in a smaller area than in real accidents. This is apart from the issue of the low incidence of impacts with rigid convex objects. As most helmet manufacturers optimise their products to pass the National standards, it is possible that the helmet design is not optimal for the helmet users.

Our experiments show that no-shell cycle helmets can easily protect the side of the head for impacts on a flat rigid surface with an impact energy equivalent to a 30 J in a conventional helmet test rig. The maximum deflections in these tests(Table 4) show that the helmets could pass a 60 J test without the foam bottoming out. It is not necessary to have a helmet shell to pass these tests, but there must be an adequately thick layer of high yield stress foam. The PS and PP foams examined here had compressive yield stresses in the range 0.7 to 1 MPa at a strain of 10%. The necessary thickness of the foam depends on the impact energy, but a 20 mm thickness should be a minimum. For the better helmets the impact energy could be increased to the equivalent of 100 Joules into a rigid immovable anvil, equivalent to a rider falling about 2 metres and striking the side of his/her head on the road surface, and the head accelerations should still be less than 200 g.

Although the 35 mm diameter hemispherical striker test is severe it represents a not infrequent equestrian accident when a rider's helmet contacts a branch of a tree. It is of concern that the design of horse riding helmets is affected more by tradition than by considerations of head protection. The localised contact force in some of the hemispherical impact tests, calculated from a typical contact area of 500 mm^2 and a pressure of 5 MPa, is 2.5 kN. By Aldman's criterion [7] this is sufficient to cause a depressed skull fracture. However the striker lacks the sharp edges of a flat-ended cylinder, which cause high stress concentrations in the skull and promote fracture.

The rotational acceleration trace(figure 11), for a hemispherical striker impact on a riding hat, shows oscillatory signals, especially for the second impact on the unprotected headform. Very high values of the peak rotational acceleration may not mean much if the time duration is small and the mean value is low. Our results can be compared with experiments when a cadaver head, instrumented with multiple linear accelerometers, was struck laterally with a padded impactor[20]. There were similarly large oscillatory angular acceleration values for the first 5 ms of impact. These may represent a real angular shaking of the skull, or they may be instrumentation artefacts. Even if they are real they do not appear likely to cause high shear strains in the brain or in the bridging veins, since the time duration is too low. If a severe striker-to-skull impact causes the skull or the accelerometers to ring (resonate) then there will be large oscillatory signals on the accelerometers. The angular acceleration trace, calculated by subtraction of the signals of two linear accelerometers, will also have ringing oscillations. In reality the angular velocity increases on a ramp(figure 5a and 5b) to a moderate value around 20 rad s^{-1}. Experiments on boxers[21] showed that angular velocities could reach 40 rad s^{-1} without injury and the peak angular accelerations were of the order of 10^4 rad s^{-2}. Hence the angular accelerations observed here are not felt to be injurious. The experimental research on primates, which established rotational acceleration tolerances, did not involve a direct impact to the head, and therefore the angular acceleration pulses were longer and less oscillatory. Comparison on the basis of peak rotational acceleration values should not be made unless the time scale of the acceleration pulse is similar.

The research is being extended to consider higher energy impacts and impacts which are oblique to the surface of the helmet, as these should produce higher values of rotational acceleration.

5 CONCLUSIONS

1 It is possible to protect the temporal region of the skull from lateral impacts, so long as the helmet shell covers the region and there is an adequate thickness of rigid foam liner.

2 The lack of a flexible neck and torso in helmet test standards has caused the issues of head rotation and rotational acceleration to be neglected. The former changes the impact site during the impact, and the latter is a possible cause of diffuse brain injury.

3 The impact energies in helmet standards (which use rigid immovable anvils) are underestimates of the impact kinetic energy that is survivable in many types of impact.

4 There are indications that polypropylene foam is better than polystyrene foam in soft shell cycle helmets at spreading the load from a small diameter hemispherical anvil. This may be due to the higher fracture toughness of polypropylene foam.

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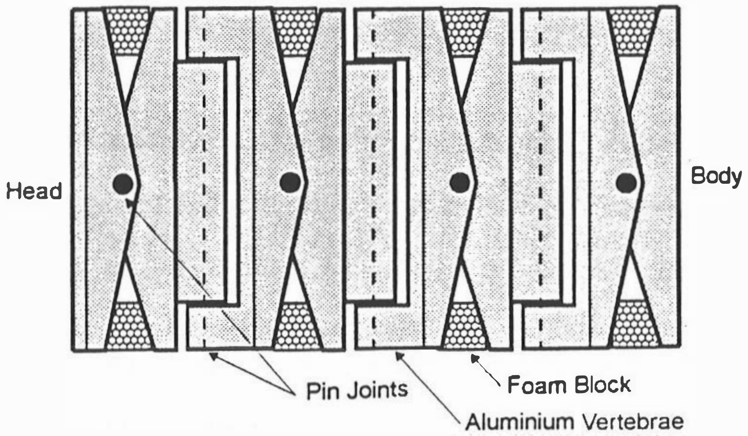

Fig. 1 Neck construction

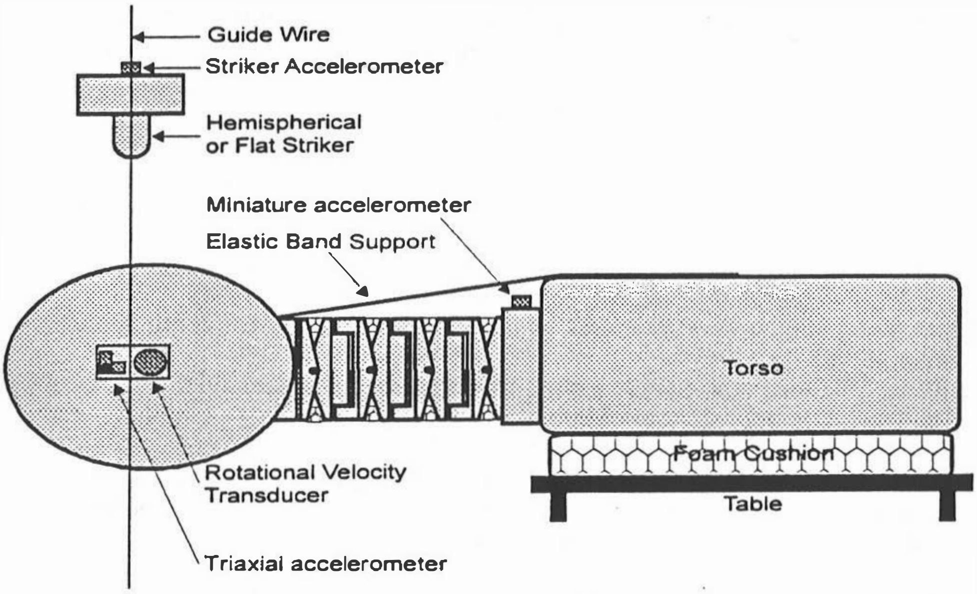

Fig. 2 The orientation of the dummy for impacts, and the positions of the instrumentation

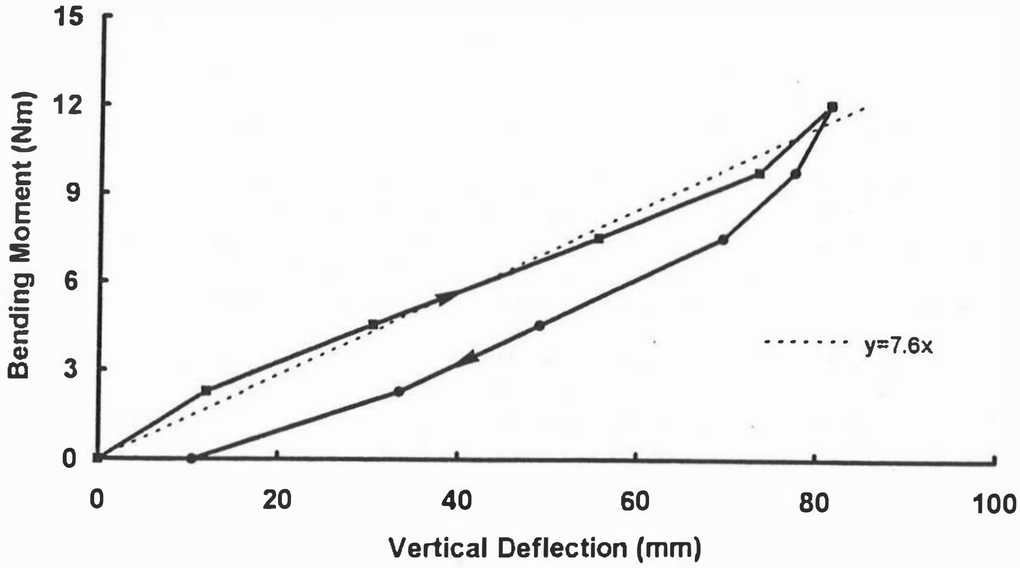

Fig. 3 Static calibration of the bending stiffness of the neck

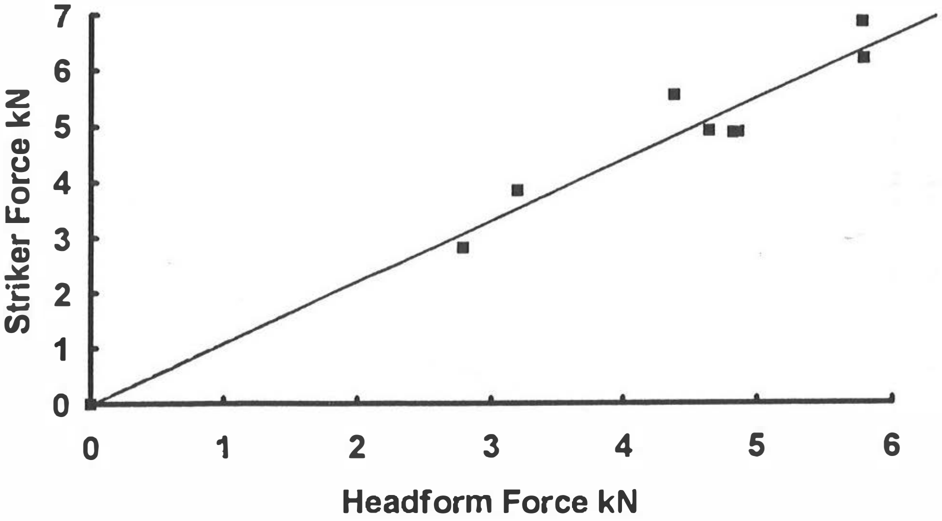

Fig. 4 Peak headform force, calculated from the peak linear acceleration, versus peak striker force.

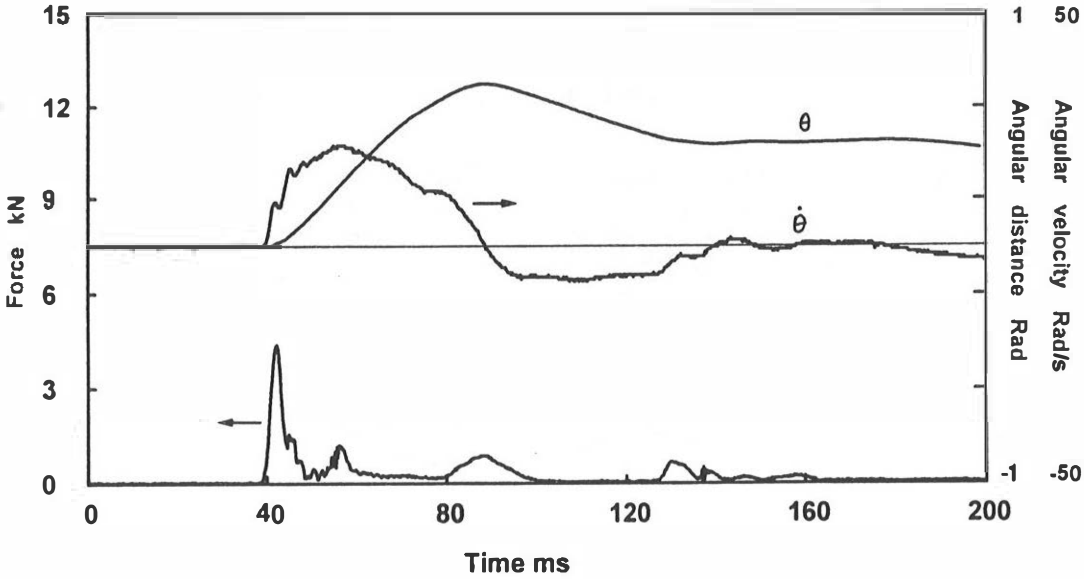

Fig. 5a Angular velocity, angular position and resultant linear acceleration versus time for a 90 J lateral impact on full face motorcycle helmet with a flat striker

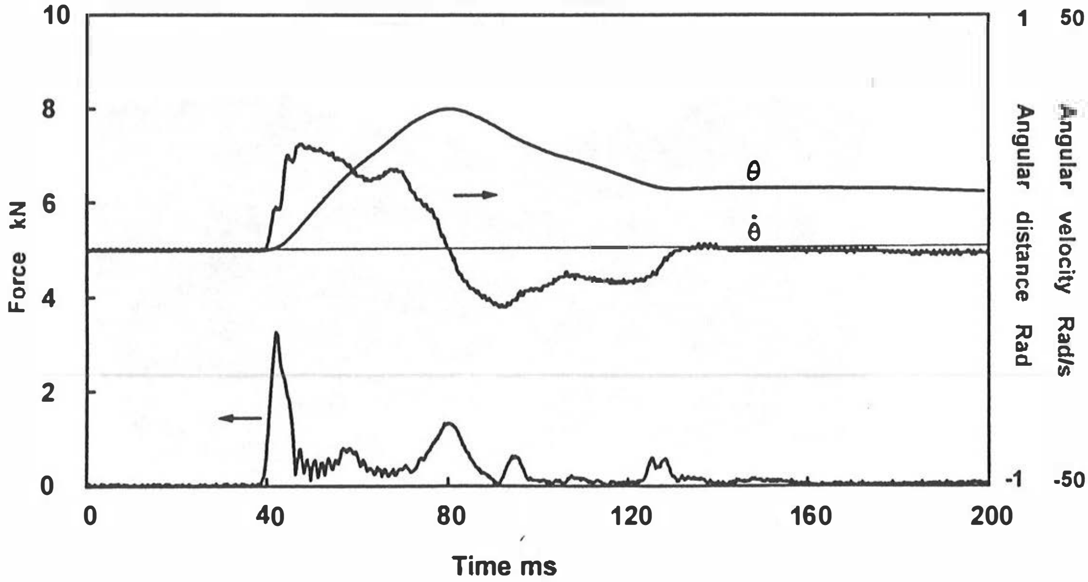

Fig.5b Ditto for a 35 mm diameter hemispherical striker

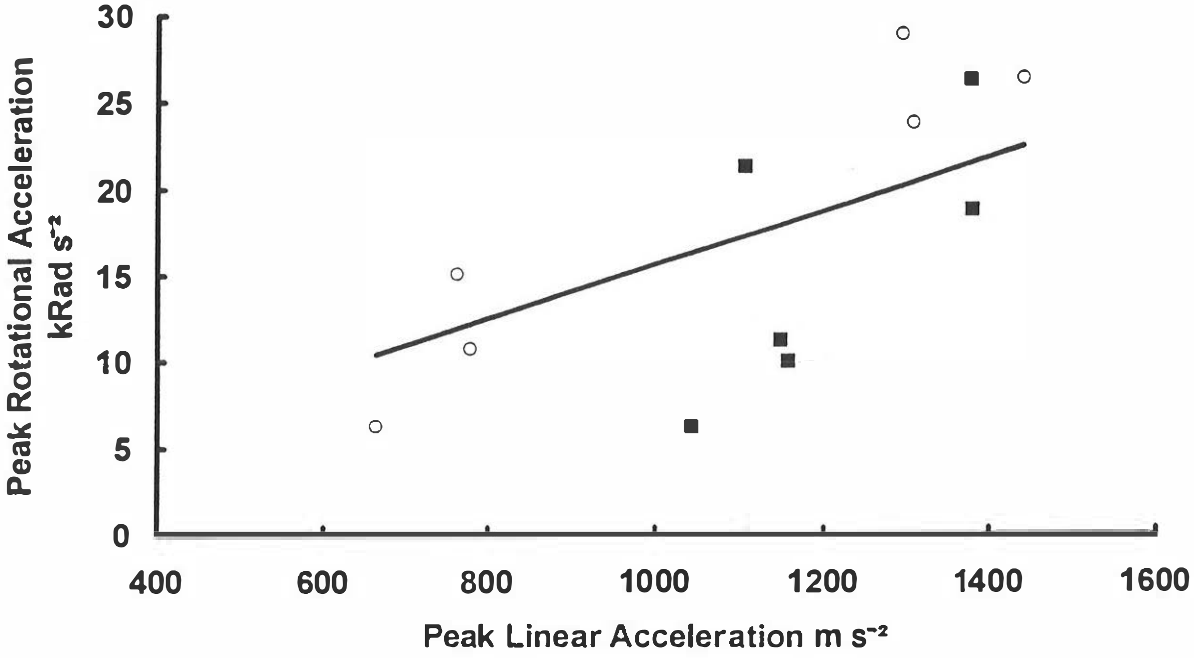

Fig. 6 Correlation between the peak linear acceleration and the peak angular acceleration in tests on a variety of types of helmet. o flat striker, + 35 mm diameter hemispherical striker

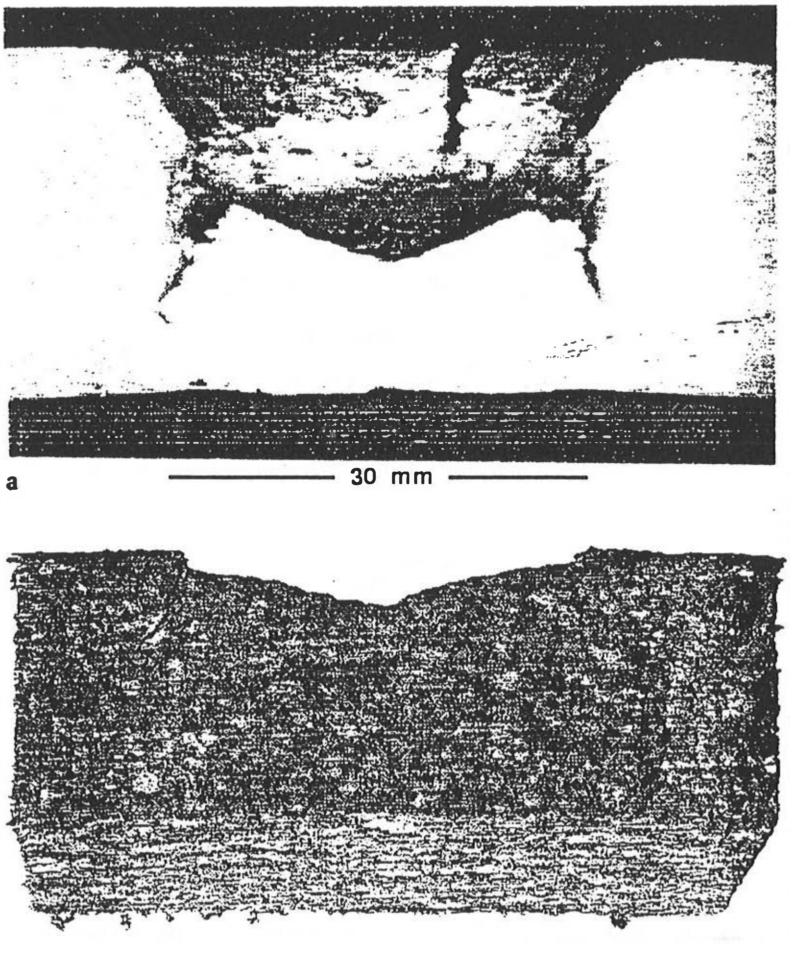

Fig. 7 Deformation patterns in a) PS, b) PP foam after impacts from the 35 mm diameter striker.

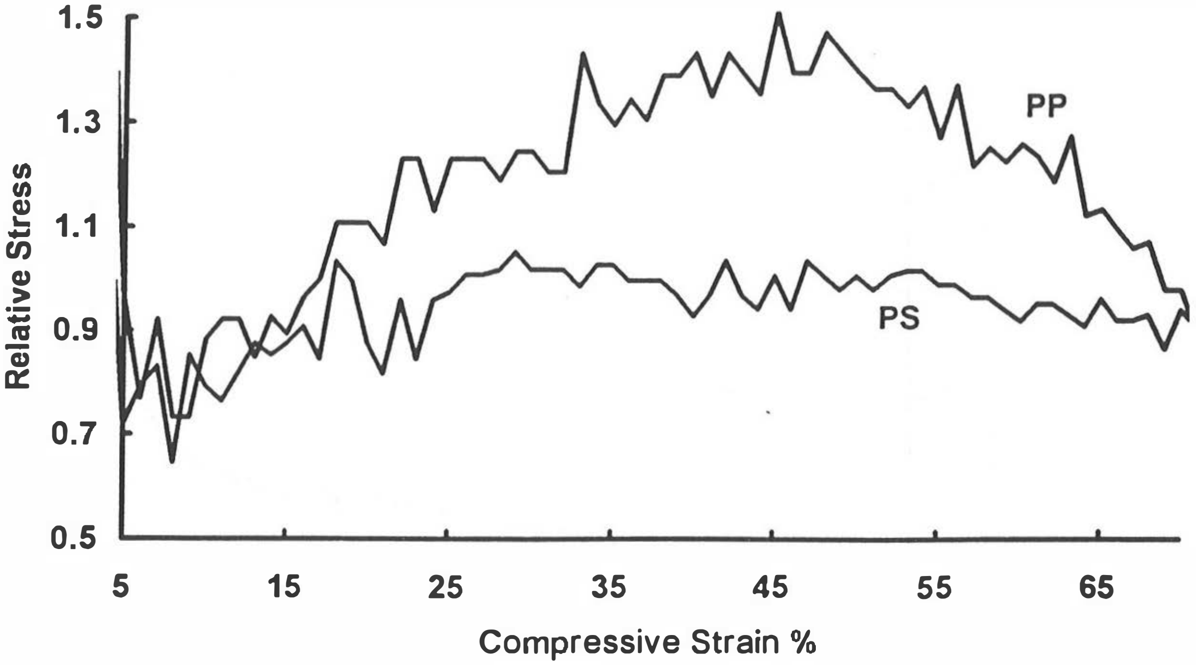

Fig. 8. Comparison of relative load spreading of PS and PP foams for a 35 mm striker impact

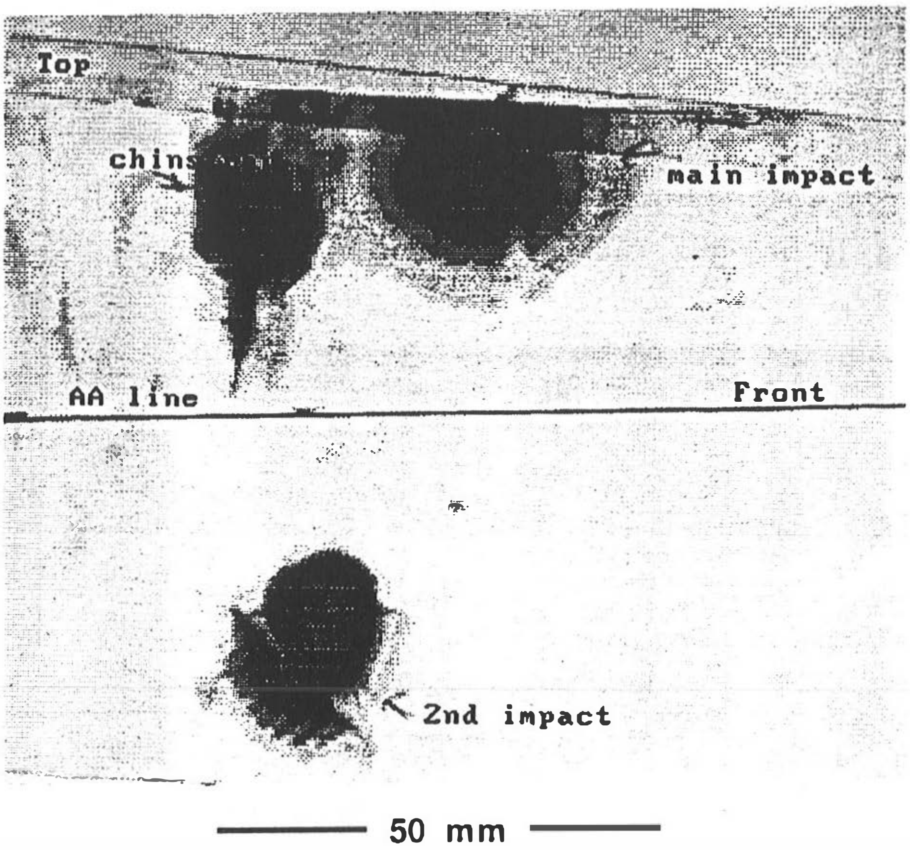

Fig 9 Fuji film trace for a 90 J hemispherical striker impact on a polystyrene cycle helmet. There are 3 separate impacts.

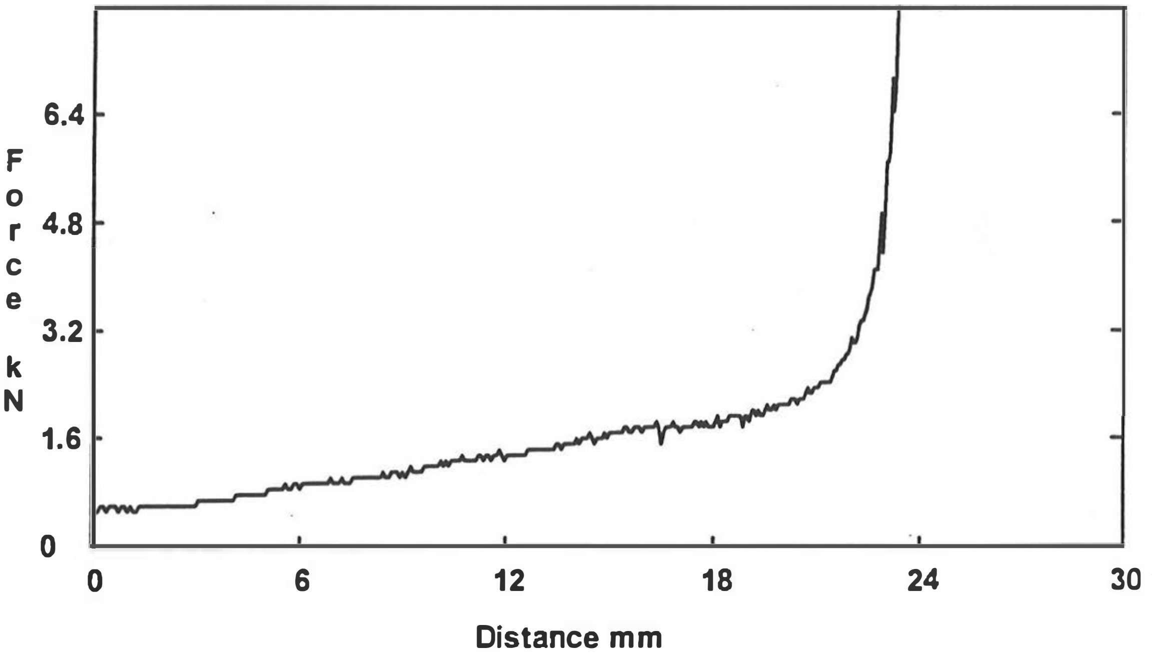

Fig. 10 Striker force in a hemispherical striker impact on a PP bicycle helmet on a fixed headform, against the distance by which the foam has deformed in the centre of the impact site.

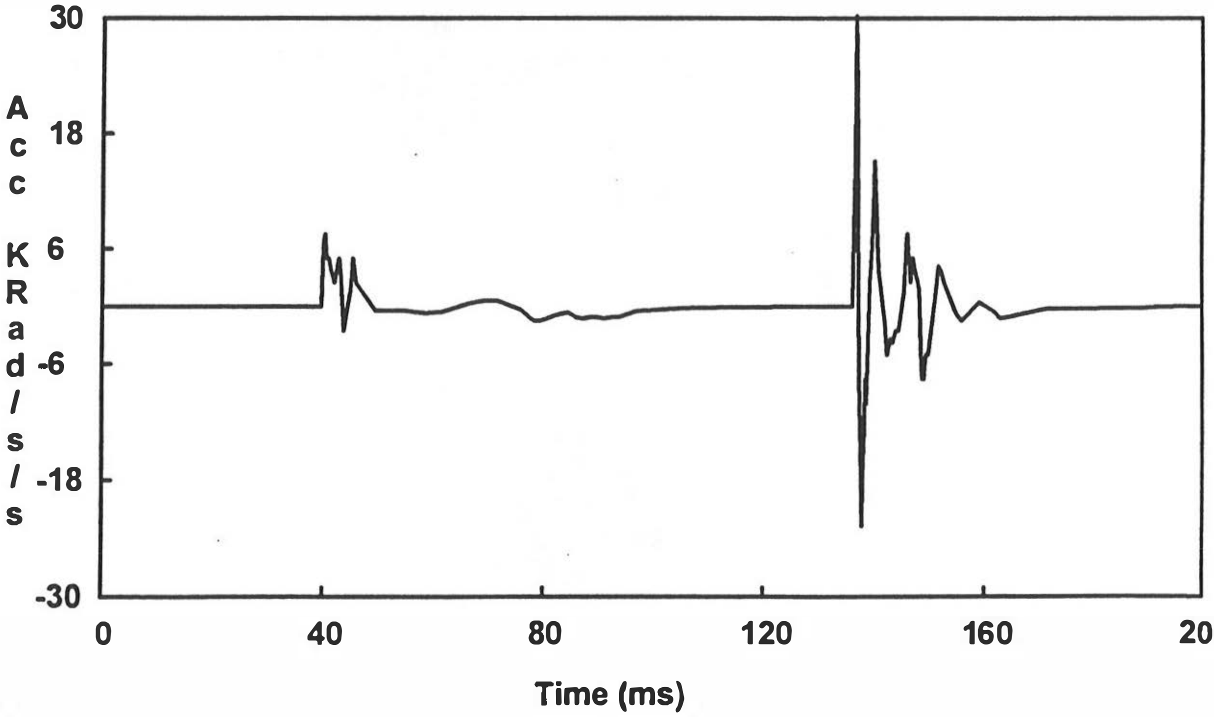

Fig. 11 Rotational acceleration trace for a hemipherical striker impact on a riding hat. There are 2 impacts and the helmet has rotated allowing the second impact to be on the unprotected headform.