THE BIOMECHANICS OF MOTORCYCLE HELMET RETENTION

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ABSTRACT

An investigation was made of the design features that lead to helmet loss in motorcycle accidents. A laboratory roll-off test showed that the position of the chin strap pivots, and the fit at the rear of the helmet were important. Analysis of the mechanics of helmet rotation showed that the initial rotation was controlled by the helmets angular inertia. The rotation angle was then limited by interactions between the helmet and headform.

INTRODUCTION

Surveys(1,2) have shown that helmet loss occurs during the accident sequence in between 10% and 30% of motorcycle accidents. The introduction of a dynamic test for the strength of the chin strap into the British Standards BS 5361 and 2495 has meant that the chin straps in helmets manufactured after 1980 no longer break in accidents. Nevertheless there is a proportion of motorcyclists who do not fasten their chin straps, and there is a proportion who wear badly fitting helmets that will come off in spite of the chin strap being fastened. It is with this last group that we were concerned. If simple design modifications can be carried out to improve helmet retention then lives may be saved at no great cost. The biomechanics of helmet retention needs to be studied to find the features that contribute to helmet loss, then a simple retention test could be added to the helmet standard that would effect improvements in the necessary areas.

Earlier investigators have listed the features that affect helmet retention as

1. the shape and size of the wearer's head
2. the shape of the interior of the helmet
3. the fleshiness of the wearer's chin
4. the tightness of the chin strap, initially and after a period of riding
5. the loading circumstances of the accident.

This is not an exhaustive list; the length, type and oiliness of the hair must also be a factor as is the retention system design. We have chosen to concentrate initially on the factors appertaining to the helmet design, and have used tangential 'impacts' in the directions that cause the largest helmet rotations.

CHARACTERISATION OF HELMETS

In the course of testing 35 different designs of helmets, manufactured in different European countries and in Japan, were tested. Only results for representative helmets will be discussed in the interests of brevity. The measurements taken that were relevant to retention were

1. Mass and angular inertia

Glaister[3] had measured the angular inertia of helmets about a vertical axis, by measuring the period of oscillation of a torsional pendulum that supports the helmet. A similar method was used for the angular inertia about a lateral axis (ear to ear), and results spanning the range of helmets are given in table 1.

TABLE 1

helmet type	shell material	mass (g)	angular inertia (kg m^2)
open face	ABS	955	0.0088
full face	PC	1160	0.0116
full face	PC	1300	0.0174
full face	GRP	1670	0.0249

The thermoplastic shells made from acrylonitrile butadiene styrene (ABS) and polycarbonate (PC) are usually lighter and of lower inertia than the glass fibre reinforced thermoset (GRP) shells.

2. Internal shape and dimensions

The inside of helmets contains a cloth lining over some soft rubbery foam used for comfort and fitting. This was ignored, since under the forces in an accident the soft foam would be completely compressed. By sectioning helmets fore-and-aft the internal profile of the hard polystyrene foam liner was found to be very close to semi-circular (fig. 1) with a radius of 115 mm if the helmet is 58 cm in circumference. The internal circumference, length and breadth were measured by firmly expanding a 12 mm wide steel band. The upper edge of this band forms a plane 88 mm below the top of the liner, and 12 mm above the 'brow' of the helmet at the front (fig. 2a). This is within 3 mm of the AA' plane used in the British Standard BS 6489 headform. It was found that the helmet sizes quoted by manufacturers (the circumference in cm) were inconsistent; some were 20 mm smaller than claimed. Therefore helmets of a minimum 580 mm circumference were selected. The length of these varied from 205 to 221 mm with a mean of 210 mm, whereas the ISO 'K' headform of 580 mm circumference has a length of 204 mm.

The fit of the helmet at the rear was measured at a position 25 mm below the reference plane of a G headform, or 125 mm below the top of the liner (fig. 2b). If there was soft foam at this level it was compressed with one thumb, and the rearwards distance measured at the back of the helmet. A gap x of 30 mm or more was chosen to represent a poor fit at the rear of the helmet.

3. Chin strap pivot position

The great majority of helmets have a single chin strap, that is usually sewn through a loop in a steel hanger plate. Sometimes the hanger plate can rotate easily on a single rivet, but usually it is fixed by twin rivets. The point at which the chin strap pivots on the shell was found by mounting the helmet on a headform in a standard position. Figure 3 shows these positions relative to a side view of the headform. Two areas of pivot positions were found later to give poor retention. These are defined relative to the dashed line joining the centre of a circle of 105 mm radius which contains the headform to the position of a chin strap under the chin. The region marked 'high' is for pivots close to the centre of rotation of the helmet on the head. That marked 'low front' is in front of the dashed line, and sufficiently low that the chin strap takes a nearly horizontal path.

4. Directness of the chin strap path

It has become common to fit soft padding in full face helmets that contacts the riders cheeks. This padding can be up to 40 mm thick, and it is not always cut away to provide a direct path from the helmet shell to the chin for the chin strap. The foam can be sufficiently stiff that it is not compressed by the usual chin strap tension (fig. 4a). Consequently in an accident, when the chin strap tension increases to the order of 1 kN, both the foam and the flesh under the jawbone are compressed (fig. 4b) allowing the helmet to be lifted by a considerable distance.

HEADFORM AND TEST RIG DESIGN

For convenience the test headform was based on one of the BS 6489 or ISO/DIS 6220 series of complete headforms, of size G with circumference 560 mm. The important features, as far as the helmet retention test, were the modifications

1. An acrylic wig of hair length 70 mm was fixed to the top of the headform. This raises the circumference to 580 mm and provides a soft interface between the helmet and the metal headform.

2. The metal under the jawline and in front of the neck was replaced by polyethylene foam of density 40 kg m^{-3}. This has the same order of stiffness as flesh and the larynx, when the chin strap tightens.

3. A wooden projection was placed in the same position as the collar bone, when the head is rotated forward. This limits the rotation of the chin bar of some full face helmets.

The dimensions of the headform were compared with NASA anthropometric data(4). The vertical distance from the top of the head to the underside of the chin was 213 mm on the headform. In different anthropometric surveys the 5th percentile head length varied from 205 mm to 223 mm with a mean of 210 mm. Therefore the length of the headform represents a low value; a person that might experience difficulty in helmet retention.

The test rig for forward helmet roll-off is shown in fig. 5. The headform is tilted downwards at 45° so the helmet tends to lift as it rotates forward. The equivalent accident situation is shown in the insert, with the linear inertia of the helmet causing it to lift, and the angular inertia causing it to rotate. The progress of the test is monitored by a quartz load cell between the 4 kg falling mass and the belt, and by angular potentiometers attached to the sides of the helmets by universal joints that can extend. In routine tests the chin strap is tightened to a tension of 20 N, then the mass dropped through 1 m until the belt becomes taut. If the helmet comes off it is deemed to fail the test. For research purposes the force and rotation signals were captured with a transient recorder and analysed with a microcomputer.

FORWARD ROTATION RESULTS

Two of the ten open face helmets, and five of the twenty four full face helmets rolled off forward in the retention test. When common design features were sought, it was found that these were poor chin strap pivot positions and poor fit at the rear of the helmet (defined earlier). The proportion of helmets in each category that failed the test was

	poor pivot position	poor fit at rear	both features	neither feature
open face	0 of 1	2 of 2	0 of 0	0 of 7
full face	1 of 3	2 of 4	2 of 3	0 of 14

Therefore there are strong indications that both of these features should be avoided. One manufacturer had modified the design of one design of helmet that was reported to have retention problems. Fitting a wedge of polyethylene foam at the rear of the helmet to improve the fit, cured the problem. Moving the chin strap pivot position on its own had no effect, but making the two modifications improved matters further.

The mechanics of helmet rotation were deduced from the force P and rotation angle records (fig. 6). There is an initial peak in the force after which the belt becomes slack when the helmet rotates more rapidly than the end of the belt. The area of this peak is the initial impulse $I = \int P dt$, which accelerates the helmet to a constant angular velocity ω. Figure 7 shows the mechanics model used. The radial distance from the centre of the helmet to the outer shell surface is r_o, and to the headform hair is r_h. There will be a total frictional force F at the helmet liner interface with the hair. Therefore the relationship between the angular impulse on the helmet and the angular momentum is

$$\int_o^{t_1} T\, dt = J\omega \qquad (1)$$

where T, the torque on the helmet, is $Pr_o - Fr_h$ and J is the angular inertia of the helmet about a lateral axis. At the end of the initial force peak the force falls to zero at a time t_1. Expanding equation (1) we have

$$r_o \int_o^{t_1} Pdt - r_h \int_o^{t_1} Fdt = J\omega$$

$$\text{so} \quad I = \int_o^{t_1} Pdt = \frac{J\omega}{r_o} - \frac{r_h}{r_o} \int_o^{t_1} Fdt \qquad (2)$$

Therefore if the friction at the helmet hair interface is constant, the impulse on the belt will be proportional to the product $J\omega$. This was checked by tests on the four helmets in table 1. Figure 7 shows that the impulse does indeed increase linearly with the helmet angular momentum. The intercept on the vertical axis represents the frictional contribution for a helmet of zero inertia. Since the initial impact lasts 20 ms the average value for the frictional force F is 100 N. The slope of the line in fig. 7 should be $1/r_o$ or 6.6 m^{-1}. In fact it is 4.3 m^{-1} which may indicate that the helmet lifts slightly during the test, or that the analysis is approximate.

REARWARDS ROTATION

Some rearwards helmet retention tests were carried out with the headform mounted horizontally, face upwards. They simulate an oblique or sliding impact of the helmet with a vehicle or the road surface. None of the helmets came off rearwards, rotation being limited by the back of the helmet hitting the neck. The rotation angles were high. In order to correspond with the severity of oblique impact tests on rough surfaces(5) the rotation angle was calculated when the impulse from the belt was 10 Ns. (It had been found that the typical tangential impulse when a headform plus helmet made an oblique impact at 10 m s^{-1} was 10 Ns). The rotation angles were

	N	mean rotation angle	straps
open face	10	63°	chin
full face	15	58°	chin
full face	3	52	chin and nape
jockey	1	31	Y to 2 points on shell

The rearwards rotations are surprisingly large. The position of a single chin strap must be a compromise for resisting forwards and rearwards rotation. Only when twin strap systems are used does the possibility of good retention in both directions arise. The addition of an auxiliary strap that passes on loops around the nape of the riders neck assists in preventing forward roll-off; however it does not improve rearwards retention markedly. Y strap designs, used by the police, army, and jockeys, do allow the two types of rotation to be dealt with separately. The chin strap has two branches, that are secured to the shell at widely spaced points forwards and aft.

DISCUSSION

A simple, low cost, helmet retention test has been described that will be included in the new British Standard for vehicle user's helmets, to be issued in April 1985. It is capable of distinguishing helmets with poor design features that were known to have come off in road and race-track accidents. It is obviously much cheaper than testing anthropometric dummies on a moving motorcycle. Through the analysis of the angular acceleration of several helmets in figure 7 it is capable of measuring the frictional contribution between the hair and the helmet. Thus it would be suitable for assessing the effects of hair type and condition. However there are limitations with such a simple test, and further work will need to be done to overcome them. Anthropometric surveys are needed to see the proportion of motorcyclists that are at risk from poor helmet fit, and to assess the need for a better range of helmet sizes. Oblique impacts of a dummy with a flexible neck on to a road surface are needed to assess the interaction between rotational forces and forces directed towards the centre of the head. This further work is in progress with the financial support of the Department of Trade and Industry.

Acknowledgement

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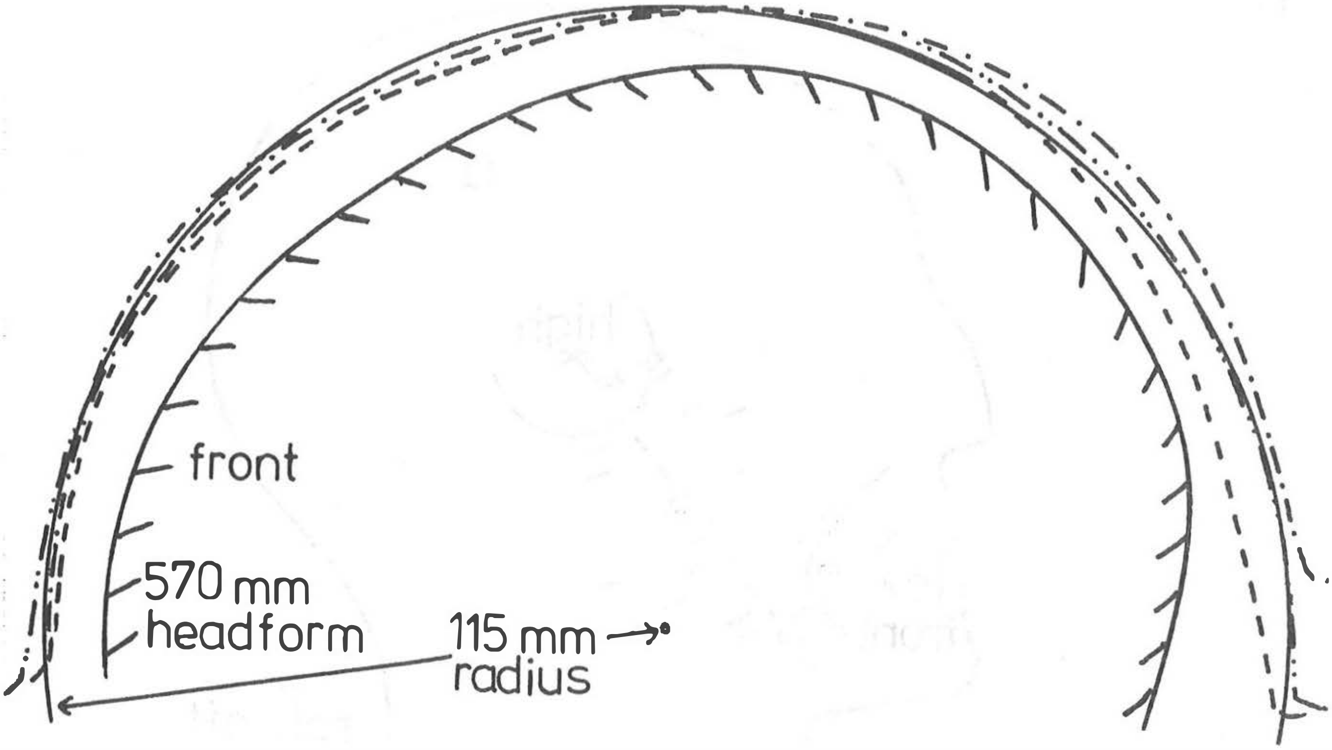

Fig. 1. Fore and aft section of the inside of helmet liners, compared with ——– 115 mm radius circle, and 570 mm 'J' headform.

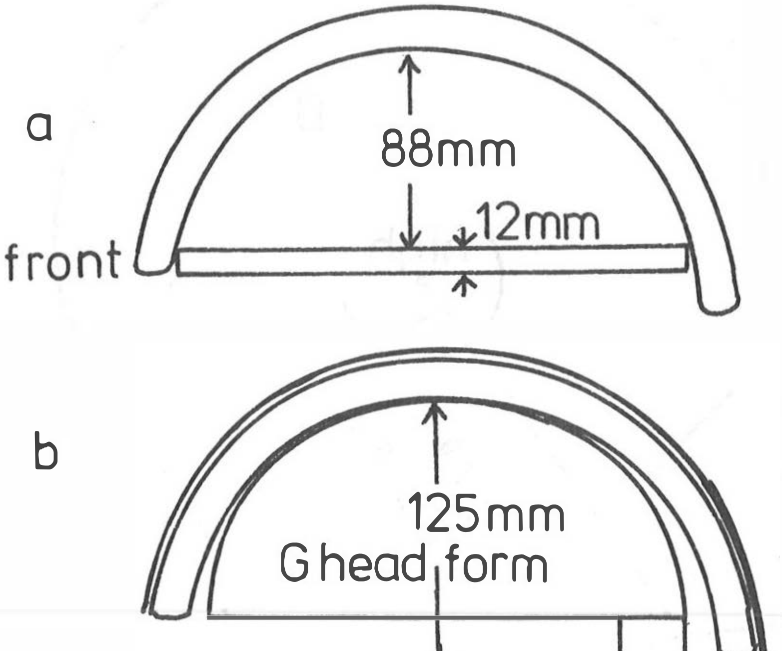

Fig. 2. Measurement of helmet a) circumference, length, breadth b) fit at rear 25 mm below reference plane.

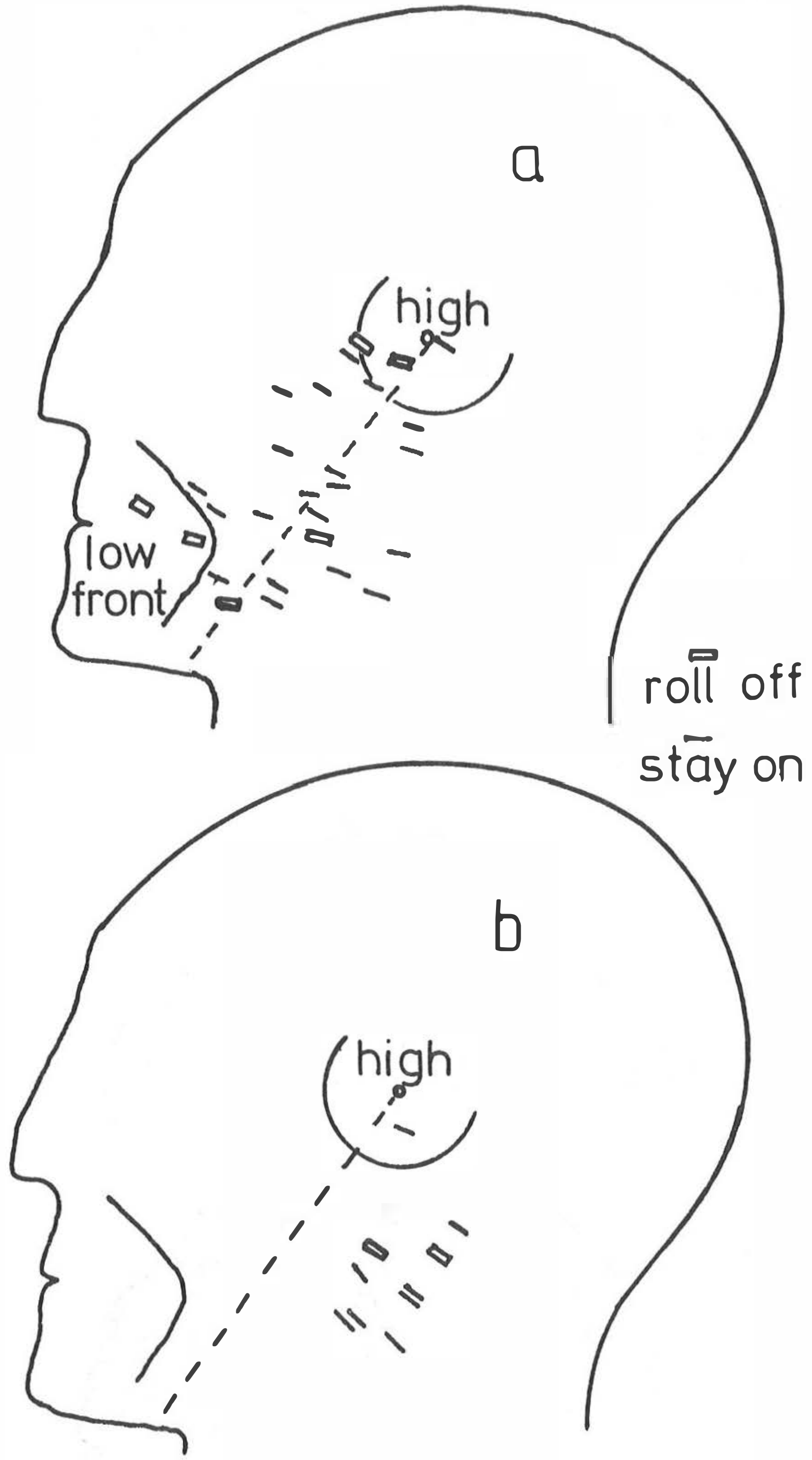

Fig. 3. Chin strap pivot positions relative to a J headform for a) full face b) open face helmets that --— stayed on, rolled off.

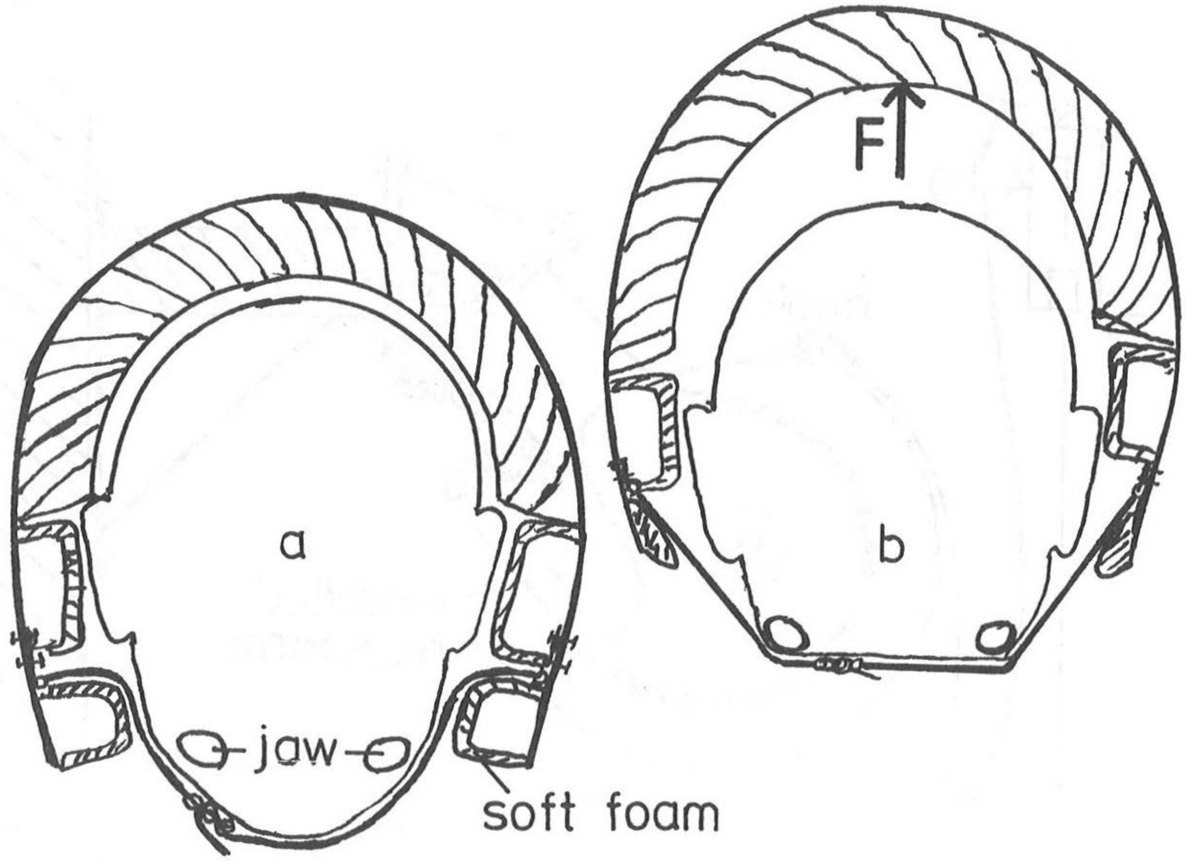

Fig. 4. Effect of soft padding at helmet sides in allowing the helmet to lift in an accident.

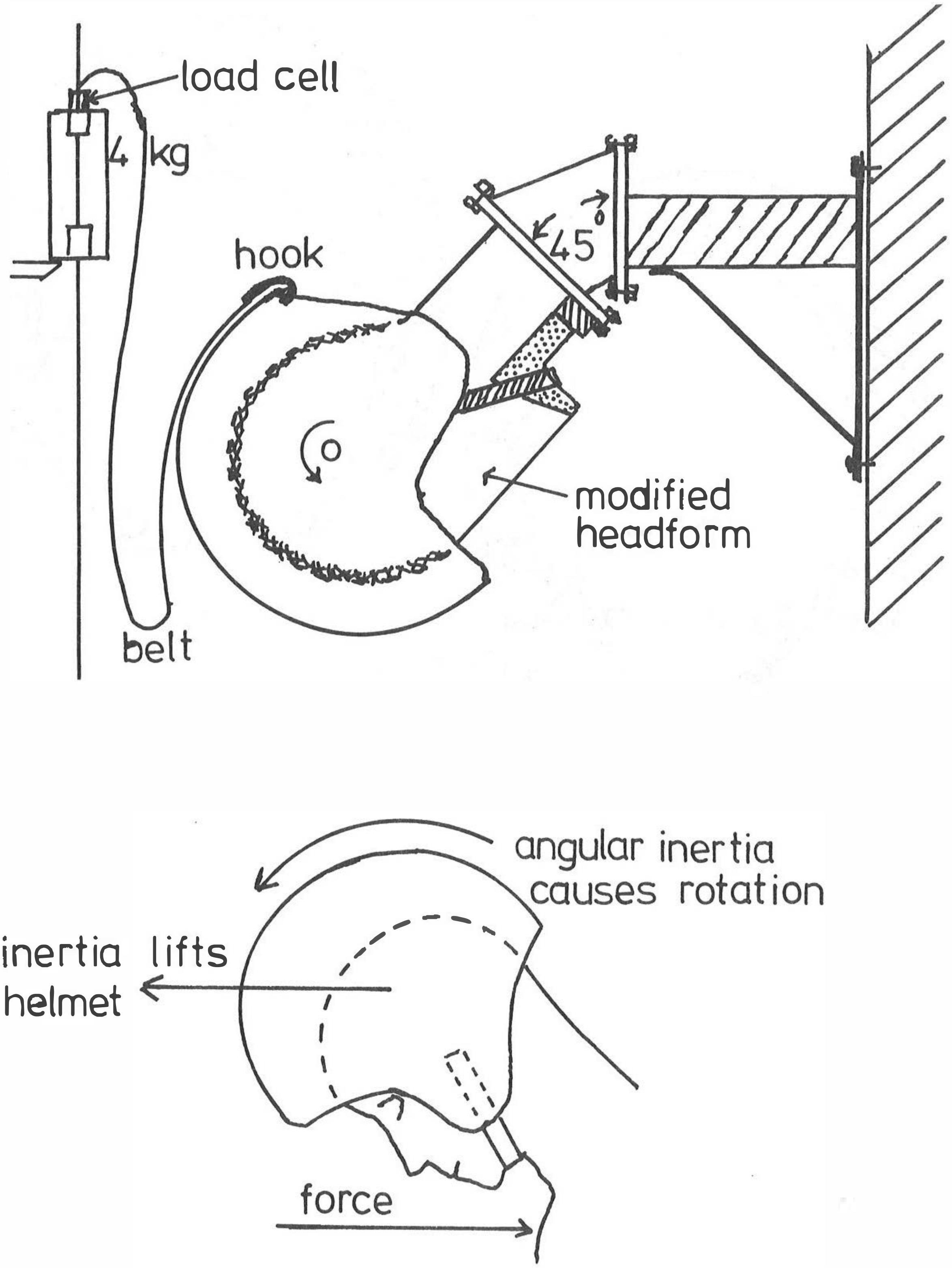

Fig. 5. Test rig for helmet forward roll-off, and simulated mechanism of helmet loss.

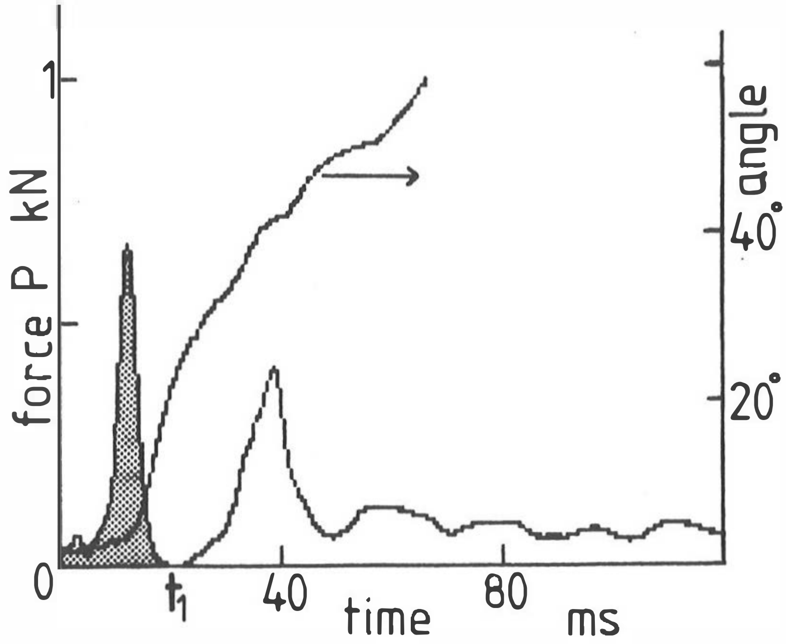

Fig. 6. Variation with time of tangential force and helmet rotation angle during roll-off test.

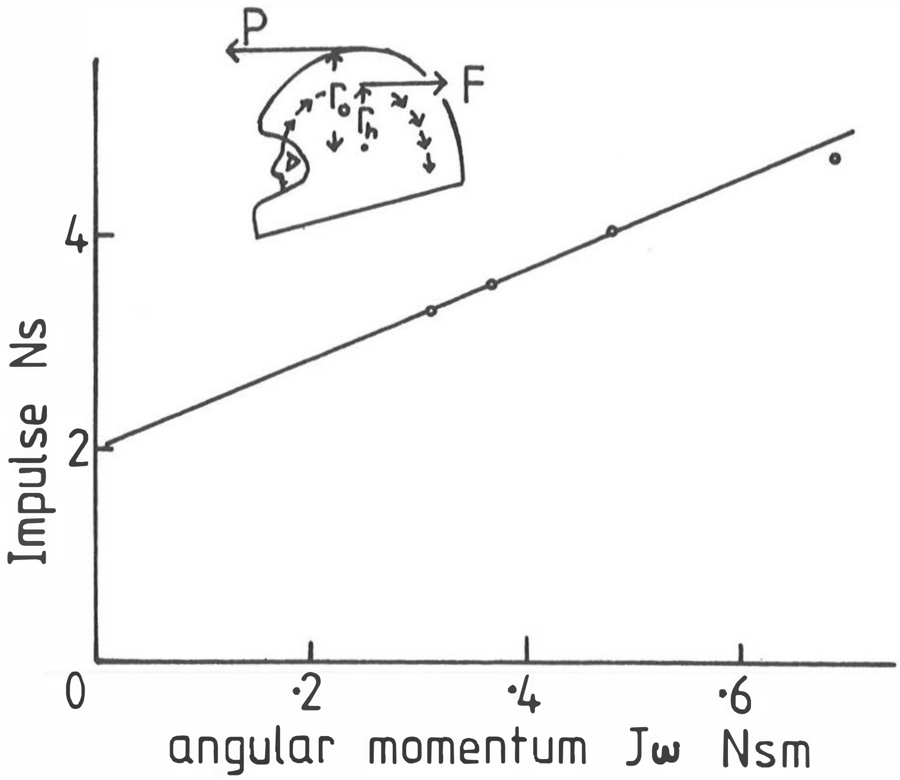

Fig. 7. Initial tangential impulse versus the angular momentum transferred to the helmet.