Impact Protection of Police Public Order Helmets

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Abstract

An instrumented head system has been constructed using a Hybrid III headform mounted on a Eurosid neck unit. A tri-axial array of nine linear accelerometers was used to enable measurements to be made of both the linear and angular accelerations experienced by the headform during impacts from a variety of missiles designed to replicate the real-life threats experienced by police officers in the course of their duties. The design, construction and validation of the system are described. The results for different helmets are presented and discussed and comparison made with other published work in related areas. It has been demonstrated that:

Very high peak angular accelerations (>10,000 radians/s^2) can occur with relatively low peak linear accelerations (120 'g').
The short duration of the acceleration results in low angular velocities (25 radians/s).
The peak acceleration and velocity values vary as a function of the impact energy and impact momentum for different types of helmet.

Introduction

The Police Scientific Development Branch (PSDB) of the United Kingdom Home Office has responsibility for advising the Police Forces of England and Wales on a wide range of equipment. One group within PSDB is responsible for protective equipment for Police Officers involved in public order duties (policing demonstrations, football matches, etc.).

This paper describes a system built to assess the impact performance of protective helmets and some results obtained from it. The work is part of a project to produce a minimum performance specification for a Police Public Order Helmet. The requirements for a public order helmet are wide-ranging and include protection from the effects of blunt impacts, penetrating objects, petrol and other inflammable and corrosive liquids. The helmet must allow the officers to see and hear what is happening around them, and have an adequate retention system. At present there is no standard that covers protective helmets for this application; the helmet used by the majority of police forces is tested to the impact and penetration sections of BS 1869:1960, a former UK motorcycle standard.

The ultimate aim of this work is to define an impact test, or tests, for the minimum performance specification that will discriminate between helmets which provide an adequate level of protection, and those that do not. It was decided that a system should be built to bridge the gap between the real-world threats faced by police officers, and the more abstract types of tests that are commonly used as performance indicators for helmets. This system would enable investigation of the protection provided by helmets from a range of impacts in a manner that was both reproducible and also sufficiently life-like. The results from this system could then be used to determine an appropriate impact test to reflect the requirements of public order policing. The range of threats faced by officers is almost infinite, from thrown coins, stones, bricks, iron bars, lengths of wood, to a refrigerator thrown from a multi-storey building. It is clearly impractical to provide head protection against the refrigerator, and the primary requirement for impact protection was taken to be against hand-thrown missiles weighing between 0.25 - 2 kg, travelling at between 15 - 30 m/s.

The PSDB Instrumented Headform

Head injuries can arise from a wide range of different causes that result in a number of separate classes of clinical injury [1, 2]. The impact section of a helmet standard is intended to indicate the level of protection provided against "closed head" injuries such as concussion, subdural haematoma and diffuse axonal injury and excludes injuries such as skull fracture or puncture wounds. For "closed head" injuries it was apparent [2] that the principal quantities that should be measured to assess the performance of a helmet were the linear and angular accelerations and velocities induced in a headform by the forces transmitted through the helmet from an impact.

For the results from this system to be comparable with published results, the headform needed to be a recognised standard anthropometric unit, and a high degree of bio-fidelity was desirable to make the results relevant to real-life. In addition it had to be sufficiently robust to withstand the impacts described without damage, and be compatible with the chosen method of measuring the accelerations and velocities. The Hybrid III headform and the EuroSID neck were selected as the most suitable with which to build an instrumented system [3, 4]. The neck unit was securely attached to a concrete block; the response of the remainder of the body has no significant effect on the accelerations and velocities of the headform because of the short time duration of the impacts.

The measurement requirements for the motion of the headform were defined on the basis of previous work [5, 6, 7, 8, 9]:

Linear acceleration	500 'g'
Angular acceleration	5000 radians/second^2
Measurement bandwidth	10 - 1000 Hz.

To enable the system to measure any general motion of the headform, the accelerations and velocities needed to be measured about three orthogonal axes. The linear acceleration of the headform could be measured using a tri-axial linear accelerometer. Measurement of the rotational motion was not so simple, and four different methods of measuring it were considered:

- Calculation from applied force and location measurements
- High-speed photography or video
- Direct angular acceleration transducers
- Array of linear acceleration transducers

Without making very broad assumptions about how the helmet transmitted the force to the headform, it would be impossible to calculate the headform motion from force and location measurements. Given that these were the qualities which were to be compared in this study, this approach was ruled out.

It was decided that high speed photography of the motion of the headform about three axes, followed by digitising and analysing the results, was too complicated and expensive. A further reason for rejecting this method was that it gave head displacements rather than head accelerations. Although in theory double differentiation of the displacements should give accelerations, in practice this would require high filming rates and very precise measurements to minimise the effects of noise on the measurements [10].

Three angular acceleration transducers were considered: the Endevco 7302BM2, Endevco 7302B and Kistler 8832TAP, but none of these were suitable for this application. The Endevco 7302BM2 was the closest to the requirement but had an inadequate frequency response (10 - 200 Hz) compared with SAE class 1000. The device's linear shock limit (300 'g'), and its size also made it unsuitable. The 7302B device was not sensitive enough and its frequency response (1 - 600 Hz) did not meet the requirements. The Kistler 8832TAP combined an angular and a linear accelerometer in one unit, and had an acceptable angular acceleration measurement range. However, the quoted linear acceleration range and shock limit (18 'g') were inadequate for these impacts. More recently a range of Magnetohydrodynamic angular velocity transducers have appeared which might have been suitable for this application [11].

The chosen method was to use an array of linear accelerometers, as this was the only way of producing a system with sufficient bandwidth, sensitivity and durability. This method had several disadvantages as it did not directly measure the desired quantities, involved collecting data from between nine and eighteen channels of data instead of six (3 angular and 3 linear acceleration channels) and required significantly more processing of the data to extract the results.

Design and construction of the linear transducer array

A variety of different configurations have been proposed and analysed for an array of linear acceleration transducers that can measure the angular acceleration of a rigid body. A number of working systems have been built and tested [12, 13, 14, 15]. It was decided to use the 3-2-2-2 arrangement of nine transducers suggested by Padgaonkar [14]. This configuration was selected as the simplest in terms of processing and construction, and in addition there was knowledge of a similar system that had already been built and used to measure the motion of a headform when punched by boxers [5].

Some of the sources of error that have been identified for these arrays [13, 16, 17, 18] include those that result from:

The transducers not being accurately and rigidly mounted
The results of cross-axis sensitivity in the transducers
Noise and measurement error from the transducers

An additional constraint on selection of the transducers was that they should be small to fit within the headform. Endevco 2228 tri-axial accelerometers were selected as they met these requirements and were in a package that could be accurately mounted. In three of the four locations only two channels of acceleration data were used, and the surplus in the number of accelerometers was used when the transducers were positioned, to minimise the individual channels' cross-axis sensitivity. For maximum rigidity and precision, the transducers were mounted on a separate, removable frame made of aluminium alloy. A bolt in the threaded support in the top of the headform pressed on a cap unit fitted over the upper transducer to increase the mechanical stiffness of the structure. The transducers were located in the headform to give the longest possible base-lines to maximise the effects of angular motion on the transducers and increase the accuracy of the measurements. This meant that the measurement origin did not coincide with the centre of mass of the headform and that the linear acceleration values for the centre of mass had to be calculated from the motion at the measurement origin. The total additional weight in the headform was 300 grams.

The nine channels of data were connected via charge amplifiers (Kistler 5007 with 4.7 kHz filters) to a Nicolet 500 multi-channel data acquisition system. The channels were digitised at 25 kHz and subsequently low pass filtered to remove components above 1000 Hz and processed using FAMOS, a waveform processing software package.

Validation

A number of methods of validating linear transducer arrays have been discussed in other papers [15, 16, 18]. The fundamental problem was the difficulty in establishing an accurate method that allowed validation of the angular acceleration measurements for a general motion of the headform. Three approaches were considered:

- High-speed cine or video
- Instrumented test turntable
- Angular acceleration transducers

The use of high speed photography was ruled out for the reasons already given.

A turntable test rig has been used to validate a similar system [5]. There were two main limitations: it only validated the simple case of pure rotation about one axis, and the magnitude of the angular accelerations that could be induced in the headform was restricted by the size and mass required if the turn-table was not to resonate in the measurement range of frequencies.

The approach adopted was to validate the system over a restricted range of frequencies and impacts (10 - 200 Hz, peak angular acceleration of 1,500 radians/s^2 and 30 'g' peak linear acceleration) using the Endevco 7302BM2 angular acceleration transducer. Each axis was validated separately by impacting the headform with a foam covered 1 kg. pendulum weight striking the headform directly at approximately 2.5 m/s. As a further check an additional Kistler 8694M1 tri-axial accelerometer was mounted at a known location, and the measured acceleration from it compared with the accelerations of that point calculated from the instrumented headform system measurements. This extended the validation range to a 60 'g', 4,500 radians/s^2 impact from a blow with a rubber-headed mallet.

On the basis of these results, and the characteristics of the linear transducers, the angular acceleration characteristics of the instrumented system were estimated as:

Frequency linearity	±3% (10 - 1000 Hz)
Accuracy	±5%
Noise	±50 radians/s^2 (equivalent)
Linear acceleration sensitivity	0.2 radians/s^2 per m/s^2 about parallel axis
	0.1 radians/s^2 per m/s^2 about normal axes
Cross axis angular acceleration sensitivity	3%

Experimental Details

The impact performances of three helmets, based on measurements from the instrumented headform system, are compared in this paper. The helmets were chosen to reflect three different protective levels, as established by British Standards [19, 20]:

Helmet A - a glass fibre shell with a polystyrene liner. The helmet is sold as a helmet suitable for rally driving and other motor sports, it is tested to BS 6658:1985 part A (additional protection over the minimum part B helmet).

Helmet B - a low cost polycarbonate shelled helmet with a polystyrene liner. It is sold as a general purpose motorcyclist's helmet and is tested to BS 6658:1985 part B (the current legal minimum motorcyclists' standard).

Helmet C - a glass-fibre shell with a polystyrene liner. Sold as a public order helmet, it is tested to the impact and penetration sections of BS 1869:1960 (a motorcyclists' helmet standard).

In all cases a 0.5 kg missile with a steel hemispherical face (1.5 inches, 38.15 mm diameter) was launched horizontally from an air cannon at velocity of between 15 - 31 m/s parallel to the headform's Y axis, to strike the rear of the helmet on the 20° elevation line defined in BS 6658:1985. The helmet size was selected to match the headform (58 - 59 cm.) and each helmet model was impacted at a range of speeds; a new helmet was used for each impact.

Results

The linear acceleration, angular acceleration and velocity waveforms recorded for each helmet type at three impact energies are shown in figures 1 - 9. The impact energy was calculated from 0.5 x missile mass x (missile velocity)^2. The most obvious result from the measurements is that the magnitude of the highest peak angular acceleration values range from twice to over four times the maximum values anticipated when the system was designed (from over 9,500 radians/s^2 for helmet A to 23,000 radians/s^2 for helmet C, compared with expected values of up to 5,000 radians/s^2). The maximum peak linear acceleration values are in the expected range (100 'g' for helmet A to 330 'g' for helmet C).

The most prominent feature of all the acceleration graphs is the first negative peak. In each case, the linear and angular acceleration peaks have similar widths, of between 5 - 20 milliseconds. One feature of the angular acceleration waveforms is that, except at very low energies, the main negative peak is followed by a well-defined positive acceleration peak some 20 milliseconds later, this peak becomes increasingly apparent at higher impact energies. The positive peak is followed by a second, smaller, negative peak. When the angular acceleration figures are integrated to give the angular velocities, this succession of peaks produces a characteristic "double-U" shape, with a narrow first minima and a much broader second one. The first peak value was taken as the angular velocity associated with the peak angular acceleration. The linear acceleration peaks tend to have a much wider and less defined positive portion after their negative peak.

The peak values of the moduli of the angular acceleration, velocity and linear acceleration measurements for the different helmets can be plotted as a function of impact energy and momentum (figures 10, 11 and 12). The impact momentum was calculated from missile mass x missile velocity. The graphs of the peak linear and angular acceleration measurements are very similar. Both the helmets A and B linear acceleration values show straight line increases as a function of impact energy and there is no significant difference between them. Their angular acceleration values also lie on a straight line, but have a small constant separation of 1000 radians/s^2. Helmet C's peak linear and angular acceleration values rise more steeply than those for helmets A and B; the lines intersect at approximately 60 - 85 Joules. The peak angular velocities recorded for helmets A and B also show straight line increases with a similar constant separation, of 2.5 radians/s. Unlike its acceleration values, helmet C's peak angular velocities are similar to helmets A's over the entire measurement range, and are significantly lower than the values recorded for helmet B.

Discussion

One of the aims of this work was to construct a system whose results could be compared with results published in scientific literature. In their paper Smith et al [5] measured the motion of a similar instrumented Hybrid III headform when struck by professional boxers. The greatest angular acceleration that they reported was 874 radians/s^2 for a punch from a super heavyweight amateur boxer. The associated peak linear acceleration was 62.2 'g'. Ommaya [9] formulated provisional limits relating angular acceleration to AIS value, based on extrapolation to humans from experiments performed on Rhesus monkeys, which were:

$IF\ \dot{\Phi} \geq 30\ radians/s$ and	IF $\dot{\Phi} < 30\ radians/s$ and
$\ddot{\Phi} < 1700\ radians/s^2$ AIS 2	$\ddot{\Phi} < 4500\ radians/s^2$ AIS 0 or 1
$\ddot{\Phi} < 3000\ radians/s^2$ AIS 3	$\ddot{\Phi} \geq 4500\ radians/s^2$ AIS 5
$\ddot{\Phi} < 3900\ radians/s^2$ AIS 4	
$\ddot{\Phi} < 4500\ radians/s^2$ AIS 5	

Ommaya's figures were comparable with the limits previously proposed by Lowenhielm. Having considered two different injury mechanisms, bridging vein rupture (1974 [6] and 1978 [8]) and sub-cortical haemorrhages ("gliding contusions" 1975 [7]); from a combination of experimental work, accident reconstruction and mathematical analysis, Lowenhielm proposed tolerance limits for these injuries of:

$$\ddot{\Phi}_{max} < 4500\ radians/s^2 AND\ \Delta\dot{\Phi} < 50\ radians/s\ (1974)$$
$$\ddot{\Phi}_{max} < 4500\ radians/s^2 AND\ \Delta\dot{\Phi} < 70\ radians/s\ (1975)$$
$$\ddot{\Phi}_{max} < 4500\ radians/s^2 AND\ \Delta\dot{\Phi} < 30\ radians/s\ (1979)$$

It is clear from Lowenhielm's papers that the angular acceleration and velocity figures were to be taken as joint limits.

Figures well in excess of these angular acceleration limits have been reported, especially for measurements made from direct impacts. For example Tarrière [21] reported measurements made on boxers, in which angular accelerations in excess of 15,000 radians/s^2 and angular velocities over 38 radians/s were recorded by boxers who experienced "no evident distress". Viano et al [15] reported sled tests in which a Hybrid III dummy headform struck padded load cells and windscreens, which recorded "typical values of 4,000 - 6,000 radians/s^2 with peaks over 20,000 radians/s^2". Bendjellal et al [13] recorded values of 15,500 radians/s^2 from an instrumented Hybrid III headform impacting a steering wheel.

Other angular and linear motion limits have been proposed, which would allow higher levels of angular acceleration than those proposed by Ommaya and Lowenhielm. The values obtained from boxers lead Tarrière [21] to suggest that angular acceleration values of $\dot{\omega}$ 3ms 10,000 radians/s^2 and $\dot{\omega}$ max. 25,000 radians/s^2 would be "more justified" as limits. Kramer and Appel [22] defined a limit based on a model suggested by Newman that combined the linear and angular accelerations into a single parameter. In the case of pure rotational motion, this limit would equate a 25,000 radians/s^2 peak value with a 50% probability of permanent brain injury. The discrepancy between some proposed angular motion limits and some experimental results has been acknowledged [2, 23].

The measurements from the PSDB system lie within the range of results reported in the literature. Given the wide range of reported values and methods of interpretation, it is not completely clear how these results relate to the levels of protection provided by the helmets. Comparisons can be made between the three helmets. The peak values for the accelerations show differences that separate the two BS 6658 helmets (A and B) from the BS 1869 helmet (C) and these differences became large at the higher energy impacts. Helmet C does record lower acceleration values than the other helmets for impact energies below 70 J. There is a small, but significant, difference between the angular acceleration and velocity measurements for helmets A and B. Set against these differences, the recorded angular velocities recorded for helmets A and C were very similar. Given that in head protection it is desirable to minimise the accelerations and velocities induced in the head from impacts [24], helmet A would appear the best helmet. However this does not, of itself, indicate which, if any, of the three helmets are adequate for this application, or resolve the question of whether the additional impact performance provided by helmet A over helmet B is a luxury or a necessity.

Conclusion

This paper describes and presents results from one method of evaluating helmets for a particular area of head protection. The system that was constructed was used to compare models of helmets, and significant differences between the models were apparent. But, in addition, it is desirable to provide some absolute evaluation of the level of protection provided against impacts by these helmets, in terms of the probability or severity of injury to the wearer. However, the degree and manner in which the results from such systems, based on rigid anthropometric headforms, can be related to real-life head injuries remains unclear. Various ways of relating these measurements to injury severity have been proposed: single or multiple motion limits such as those detailed above, lumped parameter models [25, 26, 27], and finite element analysis [24, 28]. There appears to be a risk of a situation in which, because there is no consensus on how the effects of head impacts should be measured [2], interpreted or evaluated, research in this area is hampered; but conversely, without further research, it is not clear how a consensus can be formed from these disparate views.

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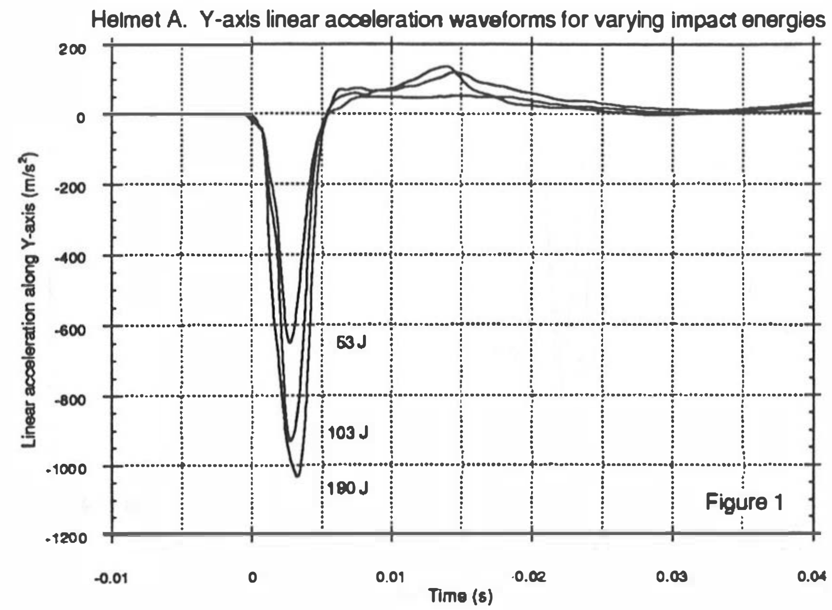
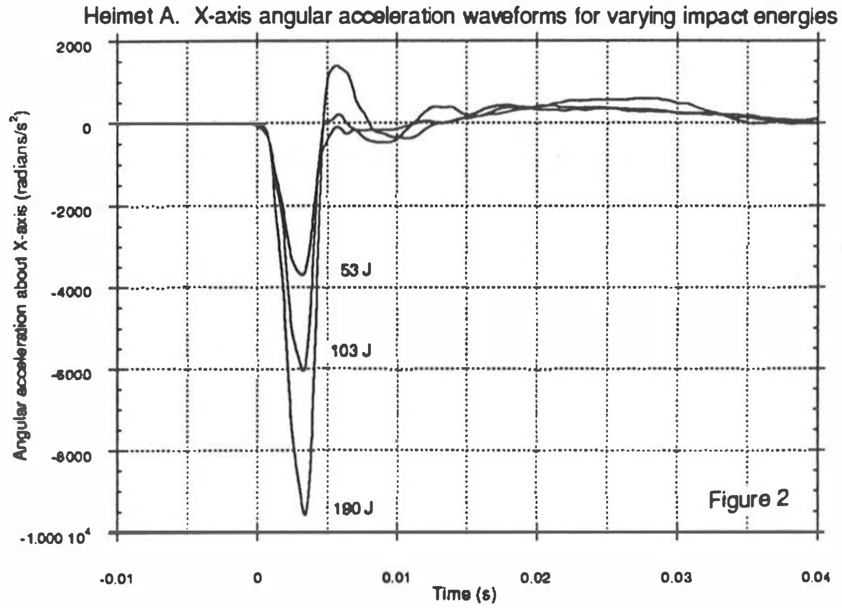
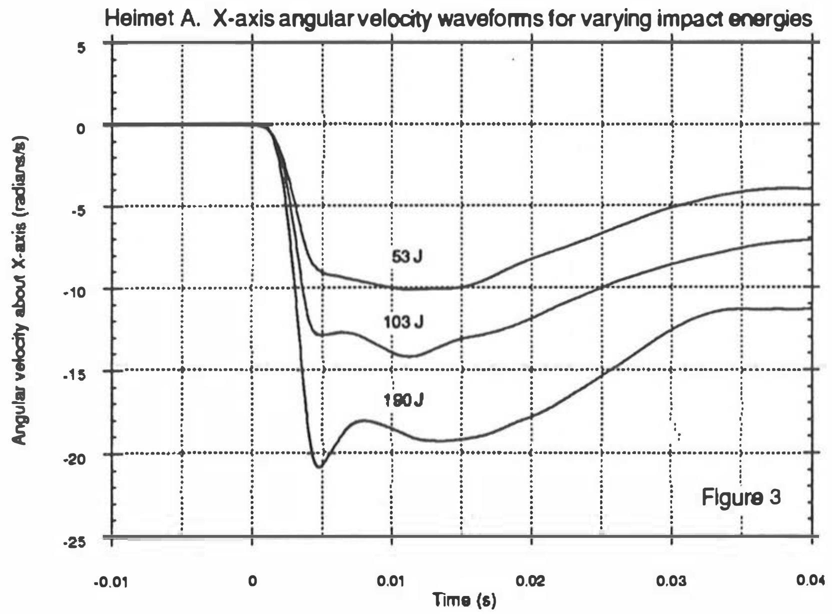
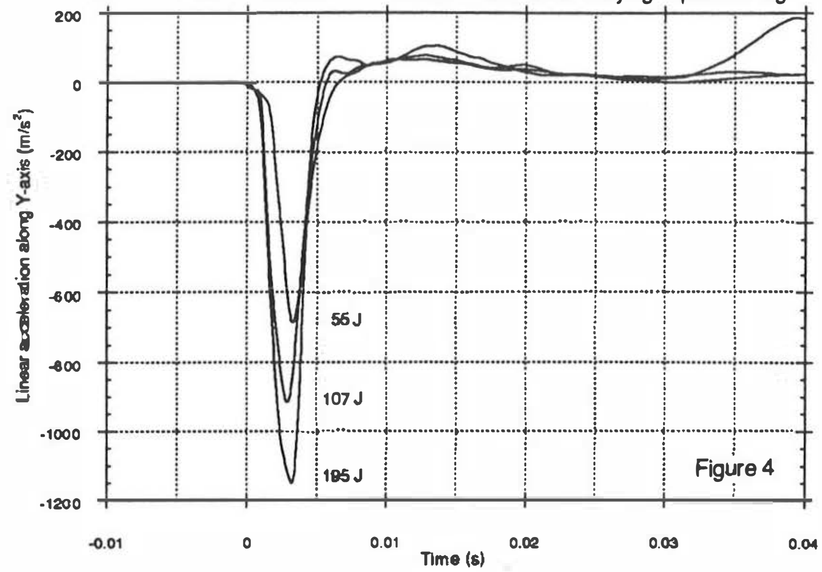

Helmet A. Y-axis linear acceleration waveforms for varying impact energies
200
0
-200
-400
-600
-800
-1000
-1200
Linear acceleration along Y-axis (m/s²)
53 J
103 J
190 J
Figure 1
-0.01
0
0.01
0.02
0.03
0.04
Time (s)

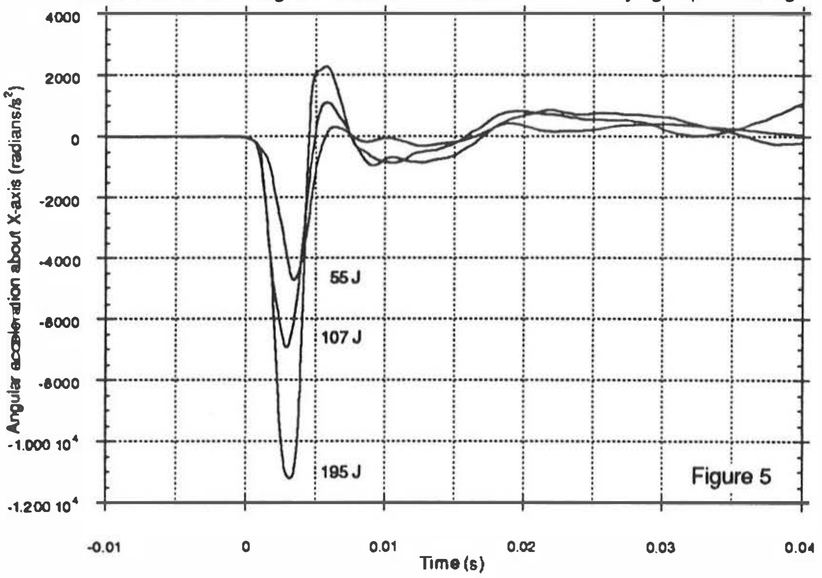

Helmet A. X-axis angular acceleration waveforms for varying impact energies
2000
0
-2000
-4000
-6000
-8000
-1.000 10⁴
Angular acceleration about X-axis (radians/s²)
53 J
103 J
190 J
Figure 2
-0.01
0
0.01
0.02
0.03
0.04
Time (s)


Helmet A. X-axis angular velocity waveforms for varying impact energies
5
0
-5
-10
-15
-20
-25
Angular velocity about X-axis (radians/s)
53 J
103 J
190 J
Figure 3
-0.01
0
0.01
0.02
0.03
0.04
Time (s)

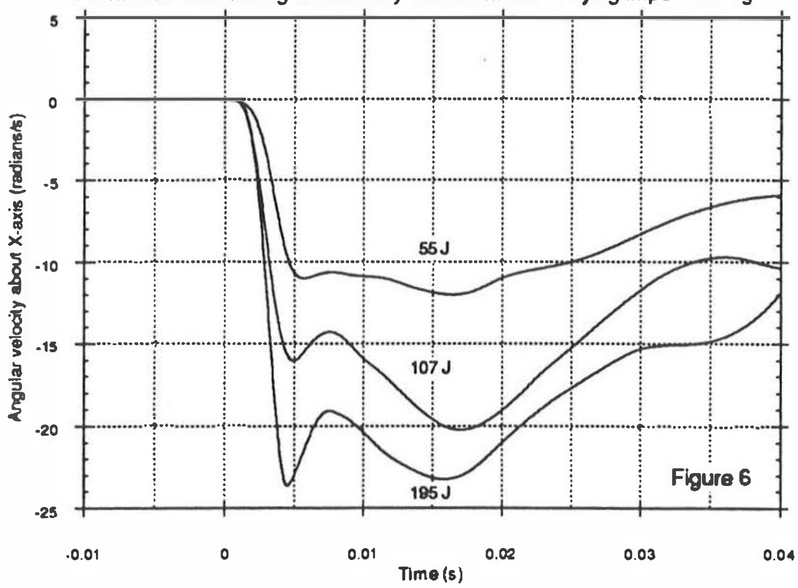
Helmet B. Y-axis linear acceleration waveforms for varying impact energies



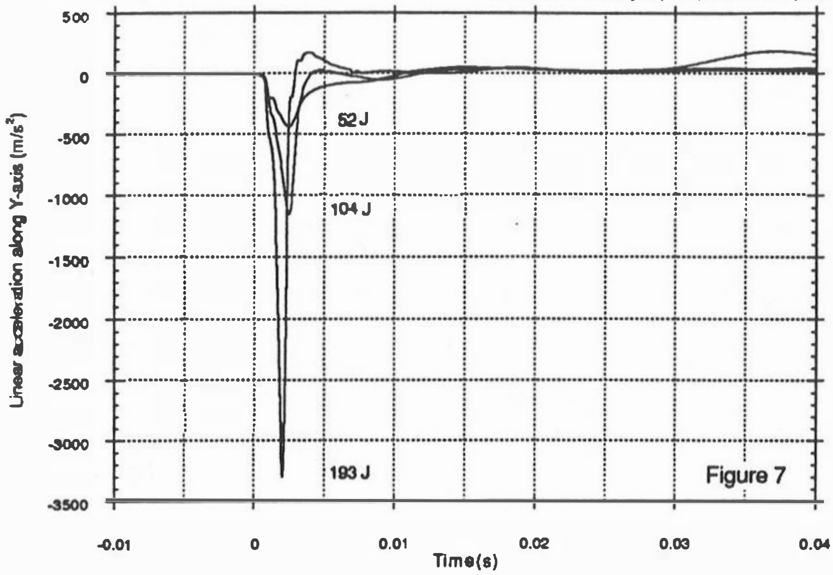
Helmet B. X-axis angular acceleration waveforms for varying impact energies



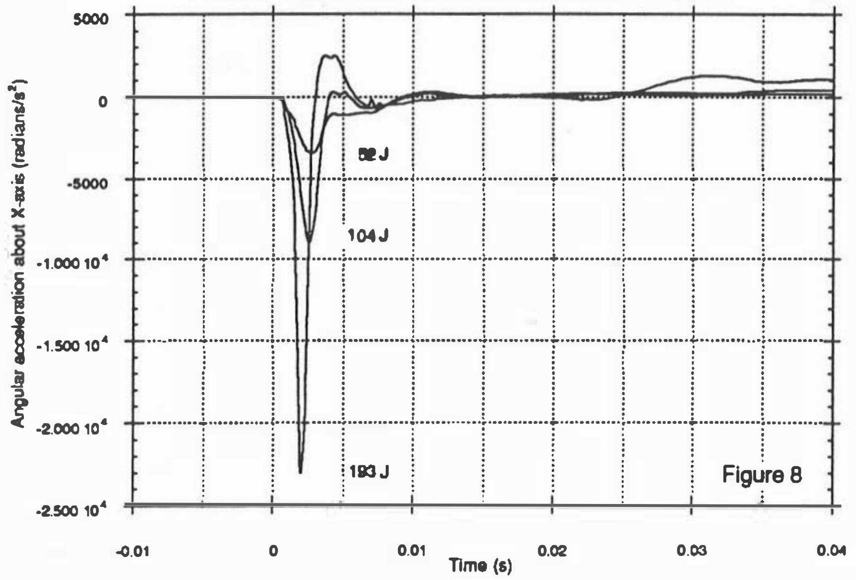
Helmet B. X-axis angular velocity waveforms for varying impact energies



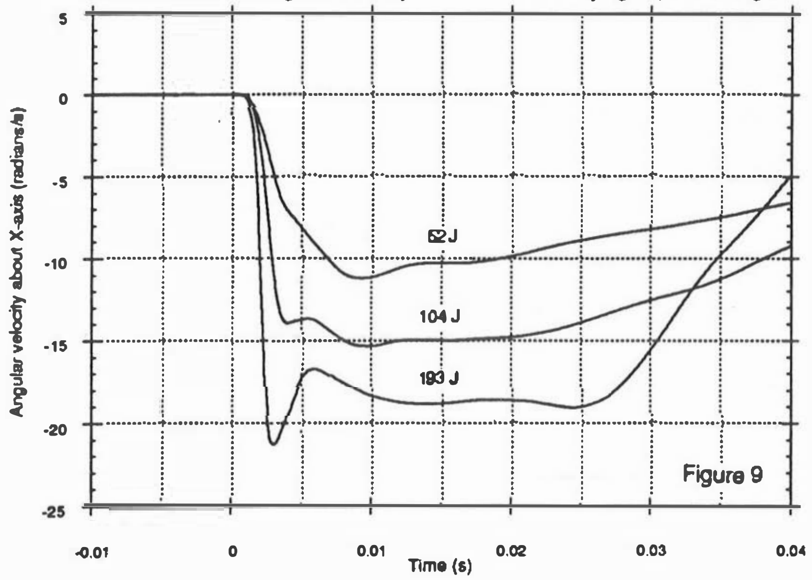
Helmet C. Y-axis linear acceleration waveforms for varying impact energies



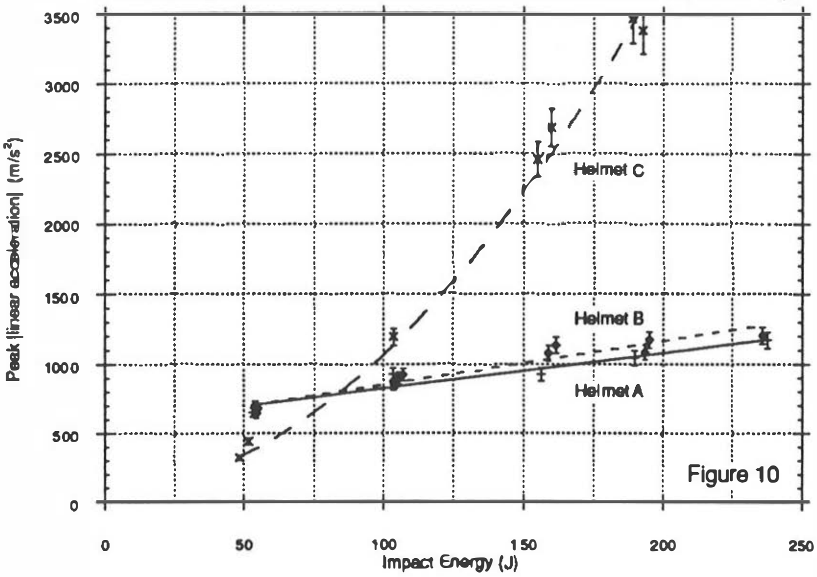
Helmet C. X-axis angular acceleration waveforms for varying impact energies



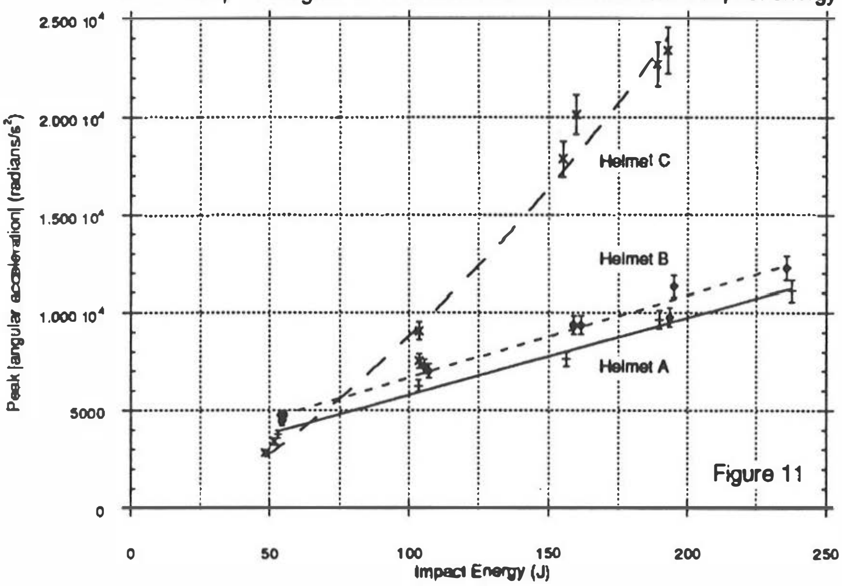
Helmet C. X-axis angular velocity waveforms for varying impact energies



Variation in peak linear acceleration values as a function of impact energy



Variation in peak angular acceleration values as a function of impact energy



Variation in peak angular velocity values as a function of impact momentum