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# THE RESTRAINT OF INFANTS AND YOUNG CHILDREN IN AIRCRAFT

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# THE RESTRAINT OF INFANTS AND YOUNG CHILDREN IN AIRCRAFT

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**SUMMARY**

In 1988 the United Kingdom Civil Aviation Authority (CAA) commissioned Cranfield Impact Centre Ltd to conduct a programme of research into the restraint of infants and young children in passenger transport aircraft. The major objective was to evaluate past, present and potential methods of restraint that would improve the levels of safety aboard UK registered aircraft.

An initial investigation showed that little work was then being conducted. The majority of previous work had been conducted in America during the period prior to the adoption of a uniform regulation for the approval of child restraints for use in automobiles and aircraft (rule published August 1984, effective February 1985). However, this work had not addressed the use of supplementary belts to secure lap carried children.

Subsequently, a programme of tests was conducted to investigate the protection offered to infants and young children carried on an adult's lap, with and without supplementary belts (infants were considered as up to 6 months of age). These tests highlighted the disadvantages of carrying a child in these configurations. In addition, tests were conducted to investigate the protection offered to young children when seated in an aircraft seat and secured solely by an adult lap belt. These tests demonstrated the inappropriateness of an adult lap belt for securing infants, but also the need to ensure that a child's body is sufficiently developed before restraining forces can solely be applied in a concentrated manner by a lap belt designed for an adult. Between the ages of 3 and 6 years, but depending on the individual child, use of an adult lap belt would become appropriate.

Alternative methods of carrying children whilst on board an aircraft were evaluated by a second programme of tests. The performance of automotive type child restraints during dynamic tests was investigated to determine if the protection provided in an automotive environment could also be provided in an aviation environment. The criteria used in these evaluations were those specified in ECE Regulation No. 44 (Uniform Provisions Concerning The Approval Of Restraining Devices For Child Occupants Of Power Driven Vehicles – 'Child Restraint Systems'). Tests with forward facing automotive restraints (for use by children weighing between 9 and 18kg) indicated some degradation in performance when these restraints were tested on an aircraft seat. But in a deceleration environment more relevant to an aircraft crash, the performance of these restraints would probably improve. The protection provided to an occupant of such a restraint would be considerably greater than that provided by a supplementary belt or a lap belt. Tests with rearward facing automotive restraints (for use by infants weighing up to 10kg) indicated that in non-standard installations, where the restraints were secured solely by a lap belt, the performance required in the automotive environment could not be achieved – even though a less severe deceleration relevant to an aircraft crash had been used.

A forward facing child seat designed for use in aircraft was tested and evaluated under the same conditions as the automotive restraints. It offered similar protection.

It was concluded that it would be feasible for the CAA to permit the use of forward facing child restraints in aircraft on the basis of an automotive test, but that it would not be feasible to permit the use of rearward facing child restraints on forward facing aircraft seats using currently accepted European automotive test criteria.

However, further analysis of the test results showed that failure to meet the forward excursion criterion did not prevent the rearward facing restraints from providing greater protection than existing restraints, provided there was no contact with a forward seat or other obstruction. On this basis it would be feasible for the CAA to permit the use of rearward facing child restraints in aircraft. Further research would be needed to evaluate the consequences of a restraint striking an obstruction during a crash.

**CONTENTS**



TABLES AND FIGURES:

## 1 INTRODUCTION

During the Spring of 1988, the United Kingdom Civil Aviation Authority (CAA), commissioned Cranfield Impact Centre Limited to conduct a programme of research into the restraint of young children, including infants*, in passenger transport aircraft.

Before commencing the investigation, the CAA indicated their wish for a comprehensive programme to evaluate past, present and potential methods of restraint that would improve the levels of safety aboard UK registered aircraft.

A four phase plan of work was devised that would:

(a) determine whether any work was currently in progress and examine the work which had previously been conducted;

(b) investigate the performance of the restraints currently available on board aircraft;

(c) investigate the performance of alternate methods of restraint;

(d) isolate, investigate and solve any problems that might prevent the adoption of means of achieving improved levels of safety for young children in passenger transport aircraft.

During the programme it was intended that the carrying of young children on an adult's lap should be investigated. The use of a supplementary loop belt to restrain a lap held young child was also to be examined. In addition, the possible use of automotive child restraints, in both forward and rearward facing configurations, was to be investigated.

The programme of work also included provision for an investigation to determine the reduction in fatalities and serious injuries to young children that could be expected if improved levels of safety were established.

At the time the programme of work commenced, some of the concerns voiced by the aviation community were typified by questions such as:

(a) whether any operational or test data existed which contradicted the school of thought that a young child was best protected whilst in the arms of a parent – on occasions it has been thought that a parent can exert 'superhuman' strength when protecting its offspring;

(b) whether any research had been done to determine if a lap-held child might be injured by being trapped in the parent's lap when the parent was thrown forward by the deceleration forces during an accident;

(c) whether a supplementary loop belt restrained a child within a safe envelope and what were the likely load distribution characteristics in the child's body and the dynamics of its head motion;

(d) whether a child over 2 years of age was adequately restrained by an adult seat belt, without additional equipment, in view of the relatively supple nature of its body as a whole and the skeletal structure in particular.

*Throughout this report, infants are considered to be up to 6 months of age.

## 2 THE SITUATION SINCE 1988

### 2.1 Literature Search

#### 2.1.1 *Data Bases*

To determine the extent of any work which had previously been conducted a literature search was conducted. The facilities of the Science and Technology Library at the Cranfield Institute of Technology were used to conduct a computer based search. Five data bases holding world-wide data were accessed,

(a) NASA STAR;
(b) National Technical Information Service (NTIS);
(c) Society of Automotive Engineers (SAE);
(d) Smithsonian Science Information Exchange (SSIE);
(e) Conference Papers Index.

The keywords that were used singly and in combination were 'accident', 'aircraft', 'child', 'crash', 'impact', 'infant', 'restraint' and 'safety'.

Additionally, the output from a previous literature search conducted by Cranfield Impact Centre on the topic of 'Child Restraints in Car Impacts' was also reviewed.

#### 2.1.2 *Findings*

Using the keywords listed above, only three appropriate references were identified by the search. All three papers were concerned with the testing of automotive child restraints under aircraft crash conditions – one of them peripherally addressed the issue of children being restrained whilst seated on an adult's lap.

However, data on child safety with regard to car impacts was found to be numerous and much of this can be usefully applied to a study focussing on aircraft safety.

A list of all the references found during the literature search is given in Appendix A. They are ranked chronologically in each of the following five subject categories:

testing of automotive child restraints under aviation crash conditions (references A1 to A3);

child impact tolerance and body dimensions (references A4 to A10);

child restraint using adult belts in cars (references A11 to A13);

dynamic testing of automotive child seats (references A14 to A21);

general aspects of child safety during impact (references A22 to A25).

#### 2.1.3 *Conclusions*

The principal conclusion to be drawn from the literature search was that little data had been published on child restraints in aircraft. That which has been published focuses on the use of automotive child seats in aircraft.

However, there was a considerable amount of information on the use of child restraints in the automotive environment and many of the implications can be directly transferred to aircraft applications. Thus, whilst the definition of tolerance limits for children remains a complex issue, the state of the art from automotive technology can be carried over to aircraft applications.

## 2.2 Airline Policies on Child Passengers

### 2.2.1 *Airlines Contacted*

The following airlines were contacted either through travel agents or direct to check-in staff:

Aer Lingus,
Air Europe,
Air UK,
British Air Ferries,
British Airways,
British Caledonian,
British Island Airways,
British Midland Airways,
Dan Air,
Monarch Airlines,
Orion Airways.

According to data from Interavia 1987, these airlines accounted for over 94% of the aircraft operated by all UK and Eire based airlines.

### 2.2.2 *Policies on Child Passengers*

Representatives of all the airlines that were contacted reported that infants from about 3 months of age onwards would be carried. Some airlines would carry unaccompanied children from age 5 years, most from age 6 years and one from age 8 years.

Unaccompanied children were under the supervision of a stewardess and seated close to the stewardess stations – unless there were too many children on a flight. Under these conditions the children were accompanied by an escort and the seating arrangements might then be different.

In 1988, on U.K. domestic routes, children over 3 years of age were required to have their own seat and use the normal adult lap belt. No additional equipment was available to improve the lie of the belt on the child – such as booster cushions used for this purpose in an automobiles. On international routes the age limit was reduced to 2 years. Children under these ages were carried on an adult's lap and no additional restraint was required. Children under these ages could alternatively have their own seat and were then restrained by an adult lap belt. However, this was at the discretion of the cabin attendants and in particular the aircraft commander, provided that in their opinion each child was 'properly secured'.

With effect from 1 November 1989, the 3 years domestic age limit was reduced to 2 years. Children under 2 years of age would be carried on an adult's lap but an additional restraint was required e.g. a supplementary loop belt. These requirements were listed in the Air Navigation Order 1989, Article 37(2)(d)(i) and are included here in Appendix B.

2.2.3 *Policies on Non-Aviation Restraints*

In 1988 representatives of the airlines gave a mixed response when they were asked about the possible use of non-aviation (automotive) child restraints.

Some said their airline would probably allow passengers to bring on-board an automotive type child seat, if it could be suitably secured solely by the adult lap belt. Others were not sure. Quite a few stated that automotive type restraints would not be allowed. One representative commented that they once did accept automotive type restraints but no longer.

Generally concern was expressed that non-aviation type restraints would cause extra demands on the cabin attendants, who would have to ensure that they fitted securely to an aircraft seat. Furthermore, there was no way of knowing whether the child restraint was serviceable nor whether it was suitable for use in an aviation environment.

In general, it was anticipated that the use of non-aviation child restraint systems might cause problems for a number of reasons e.g. administrative, installation, perceived liability if the restraint did not perform well in an emergency.

The situation has changed since 1988. The CAA issued General Exemptions to all aircraft operators, effective from 28 March 1990. These permitted the use of four named car-type seats for the restraint of children less than 2 years of age. These named seats were accepted for use only in a forward facing configuration when secured to a passenger seat by an adult lap belt. The seats could be provided either by the parents or the operators.

Subsequently, in June 1991, the CAA revised the General Exemptions for operators to use car-type seats for the restraint of young children in aircraft, so as to permit the use of seats approved to ECE Regulation 44. The accepted list of car-type seats now included those seats, as well as the four named British seats and seats approved by the FAA. All the seats were only for forward facing use by children over 6 months and less than 3 years of age.

In January 1992, the CAA further revised the General Exemptions permitting the optional use of car-type safety seats for the restraint of children in aircraft. The main features of these Exemptions were a revision of the acceptance criteria for car-type safety seats (removing the need for a list of acceptable seats) and the acceptance of a named aircraft unique safety seat. Use of the Exemptions still remained at the discretion of an operator.

## 2.3 Accident Studies

The purpose of this study was to quantify the numbers of young children fatally and seriously injured in impact accidents. Several potential sources of accident data were searched.

The World Airline Accident Summary (WAAS) was consulted but found to give a breakdown into the number of 'fatalities', 'injuries', 'no injuries', but only according to 'passenger' or 'crew'. No breakdown was given according to age, sex or seat position.

The Air Accident Investigation Branch of the U.K. Department of Transport was unable to identify any other data base of information on accident statistics for UK registered aircraft or statistics for accidents within the U.K.

It was apparent that no data were available to conduct the type of investigation that was necessary.

The only information available was that published in the Human Factors/Survival Factors Reports for aviation accidents in the United States of America (USA) by the National Transportation Safety Board (NTSB). Even here the data concerning young children were sparse in comparison to that relating to automobile accidents. Some studies were conducted with the available data, but their validity is uncertain.

### 2.4 The Situation in the United States of America

In August 1984, the National Highway Traffic Safety Administration issued a final rule allowing child restraints certificated for use in automobiles to be simultaneously certified for use in aircraft. The only additional requirement for aircraft use was that each restraint should be able to meet an inversion test to protect children from air turbulence. (This followed a U.S. Department of Transportation proposal, issued almost a year earlier, to adopt a single standard for child restraint use in both aircraft and motor vehicles).

In the case of forward facing child restraints this single standard – FMVSS 213 Child Restraint Systems – set down:

(a) excursion limits for the head of the test dummy and the knee pivots of the test dummy;

(b) resultant acceleration limits for the head of the test dummy;

(c) resultant acceleration limits for the chest of the test dummy;

(d) criteria to define whether the restraint system suffered a structural failure during impact testing.

Nevertheless, there was no requirement that children under 2 years of age carried on the lap of an adult should be restrained in any way when transported in aircraft. Nor was there any requirement that an aircraft operator accept a child restraint provided by a passenger.

## 3 TESTS OF EXISTING AVIATION RESTRAINTS

### 3.1 Objectives of the Tests

The primary objective of this programme of tests was to examine the suitability and effectiveness of the restraints currently available for use by young children in passenger transport aircraft.

In particular, this was to determine, for a forward facing aircraft seat:

(a) the maximum age of a child who can use a supplementary loop belt as a means of restraint whilst seated on an adult's lap;

(b) the minimum age of a child who can use an adult lap belt as a means of restraint whilst seated in an aircraft seat.

Nevertheless, the programme of tests was arranged to investigate the carrying of young children on adults' laps whether they were secured by a supplementary loop belt or were totally unrestrained.

## 3.2 Test Facility

The tests were conducted using the aircraft seat dynamic test facility at Cranfield Impact Centre. This consisted of a 200kg trolley running on rubber wheels along a 9.5m long track. The trolley was propelled by a number of 30mm diameter elasticated cords, which were stretched to nearly double their original length when the trolley was winched back to the release position. At the impact position, the trolley struck a 76mm diameter extruded aluminium tube which had a pre-buckled end. This predetermined the axial buckling mode of the tube and caused it to exert a controlled and repeatable deceleration force on the trolley, without a high initial peak as the tube began to collapse. By adjusting the mass of the trolley and utilising different numbers of rubber cords, the desired impact speeds and accelerations were achieved. A photograph of the facility is given in Figure 1 and shows the trolley in its pre-release position – the aluminium tube in its holder can be seen at the far end of the track.

For the programme of tests described below, an aircraft seat designed for three passengers was cut down to a 'centre single' configuration. The aluminium front legs were replaced by equivalent sized steel tubes and the suspension of the seat was replaced by sheet steel that was welded in position. The seat cushion was retained. Finally the quick release arrangement for attaching the seat to the floor track was replaced by a welded steel assembly which still allowed the seat to be moved fore and aft, to simulate different seat pitches. These changes were made to ensure the durability of the seat and to minimise any variations which the seat might otherwise have introduced into the test programme.

A seat-back was positioned on the trolley in front of the seat occupied by the test dummies so that dummy/seat back interaction could be assessed. This forward seat-back had a full rotation capability. The level of friction at the pivot points of each seat back was set so that the seat back began rotating when a force within the range 110 to 135N (25 to 30lbf) was applied at the top of the seat back.

The data collection system was of an on-board type developed by the Impact Centre. It employed seven autonomous, synchronised modules, which were programmed from a remote personal computer (PC) to set the individual gain, filter cut-off frequency and sampling rates of each module. The system was set up to measure the signals from two dummy-mounted tri-axial accelerometers and also the longitudinal trolley deceleration from a uni-axial accelerometer. The modules were triggered at the point of impact by a light source and photocell arrangement. After each test, a communications link was connected to upload the data to the PC for manipulation and graphical display. A photograph of the hardware in the laboratory is shown in

Figure 2 and a block diagram of the data collection system and instrumentation is shown in Figure 3.

One infant and two child dummies were used in the test programme. These represented a 6 month old infant and 3 and 6 year old 50th percentile children. The 6 month infant dummy was of 'bean-bag' type construction as developed by the U.S. Civil Aeromedical Institute (CAMI). The 3 and 6 year child dummies were manufactured by the TNO Road Vehicles Research Institute in Holland. (A dummy representing a 3 year old child was used because there was no commercially available dummy representing a 2 year old child). In addition, a 50th percentile adult male dummy was used during part of the programme to provide the lap on which to position the infant or child dummies.

### 3.3 Test Programme

#### 3.3.1 *General Procedure*

Two series of tests were conducted. In the first series, dummies representing a 3 year old child and a 6 month infant were used to investigate the lap-held situation. Tests were conducted with the dummies in upright and braced postures. In the second series of tests, dummies representing a 6 year old child, a 3 year old child and a 6 month old infant were used to investigate the lap belted situation.

Prior to each test the calibration of each dummy was checked and corrected where necessary (this was not possible for the 6 month infant dummy). A new lap belt was fitted to the seat and the dummy (or dummies) was positioned according to the test specification. The leads from the accelerometers inside the dummies representing 3 and 6 year old children were routed to the data recorders so as not to interfere with the kinematics of the child dummies, or the adult dummy when present. A new supplementary belt was used for each test where such a belt was required. All belts were tightened to a point which represented real life fitment i.e. there was still some slack in the belts for comfort. In practise, this was achieved by adjusting each belt so that there was 20 to 25mm gap between the belt and the dummy's abdomen when the belt was tensioned slightly by being pulled forward at abdomen level.

A high speed cine film (1,000 frames per second) was taken of each test for analysis of the dummy motions.

#### 3.3.2 *Tests with Child Dummy on Lap of Adult Dummy*

In the tests with the dummies in upright postures, the 50th percentile adult dummy was positioned on the aircraft seat and secured by a lap belt. The child (or infant) dummy was then positioned on the lap of the adult dummy – no attempt was made to position the arms of the adult dummy so that they clasped the child dummy, due to the difficulty of achieving the same pre-test conditions in a repeatable manner. This 'unclasped' configuration could be considered a worst case situation.

A pre-test position of the 3 year child dummy restrained with a supplementary belt is shown in Figure 4. Note the position of the buckle of the supplementary belt on the abdomen of the dummy. In Figure 5, the forward movement allowed by the attachment of the supplementary belt to the adult lap belt can be seen. Note that the supplementary belt does not lie on the pelvis of the child dummy, unlike the lap belt on the adult dummy.

A pre-test position of the 6 month infant dummy restrained with a supplementary belt is shown in Figure 6. Again, note the position of the buckle of the supplementary belt.

During the tests when the dummies were in a braced position, the child (or infant) dummy was first positioned in the braced posture. The torso of the adult dummy was then rotated forward onto the child dummy and its wrists were tied to the framework of the trolley. The breaking strain of the hand-ties was chosen to be the minimum necessary to hold both dummies in position during the acceleration phase of the trolley motion but which would then break due to the motion of the dummies when the trolley was decelerated.

A pre-test position of the 3 year child dummy and adult dummy is shown in Figure 7. In this instance the child dummy is unrestrained. Note that the head of the child dummy is in contact with the forward seat-back, preventing a full brace position being achieved either for it or the adult dummy. (Had a dummy representing a 2 year old child been available this situation would still have occurred, though to a lesser extent).

The following orientations and restraint configurations were assessed for the infant and child dummies:

(a) 737mm (29 in) seat pitch:

- (i) adult dummy with infant/child dummy unrestrained, dummies upright;
- (ii) adult dummy with infant/child dummy in supplementary belt, dummies upright.

(b) 914mm (36 in) seat pitch:

- (i) adult dummy with infant/child dummy unrestrained, dummies upright;
- (ii) adult dummy with infant/child dummy in supplementary belt, dummies upright;
- (iii) adult dummy with infant/child dummy unrestrained, dummies braced;
- (iv) adult dummy with infant/child dummy in supplementary belt, dummies braced.

Tests with the dummies in a braced position were only conducted with the larger seat pitch. At the smaller seat pitch the proximity of the forward seat back caused the dummies to have a near upright posture.

### 3.3.3 *Tests with Child Dummy Restrained by Adult Lap Belt*

In these tests, a dummy was positioned on the seat and secured by a lap belt which had a controlled amount of slack. However, in the case of the 6 month infant dummy, it was not possible to tighten the lap belt sufficiently. The amount of slack amounted to between two and three times the controlled slack used with the 3 and 6 year child dummies. A pre-test position of the larger child dummy can be seen in Figure 8.

The following configurations were assessed for each dummy at 737mm (29 in) seat pitch:

(a) upright posture;
(b) braced posture.

During the tests when the dummies were in a braced position, the wrists of the child dummies were tied to the framework of the trolley in the same manner as the wrists of the adult dummy were tied in the first series of tests.

## 3.4 Results

### 3.4.1 *Velocity and Deceleration Achieved*

The average velocity change of the trolley during the tests was 9.2m/s (30.3ft/s) and a typical deceleration pulse of the trolley is shown in Figure 9 (time zero in Figure 9 corresponds to the instant of first contact between the trolley and the aluminium tube). These levels of deceleration and velocity change were considered sufficient severe for the purposes of the test programme.

The upper body motion of each dummy had some influence on the exact shape of the deceleration curve from each test, but was not so great as to prevent a meaningful comparison of the results of each test.

### 3.4.2 *Test with Upright Unrestrained Lap Held Dummies*

In the tests where the dummies had initially upright postures but were unrestrained, the child (or infant) dummy moved forward on the lap of the adult dummy as the trolley decelerated, so that the back of the child dummy was not in contact with the adult dummy's torso. The feet of the infant dummy first contacted the forward seat-back and the infant dummy then rotated about this contact. In the case of the child dummy, its lower legs first contacted the seat-back, the knees bent almost double and whilst the torso rotated about the hips, the whole dummy rotated forward about the contact with the forward seat-back. In all cases, regardless of seat pitch, the adult dummy, rotating forward from the hips, struck the infant or child dummy, knocking it down onto the rotating forward seat-back and preventing further forward motion. Subsequently, the trajectories of the infant and child dummies were uncontrolled. In some instances, the infant or child dummy fell back into the legs of the adult dummy, whilst in others it fell sideways and landed either clear or partially off the trolley.

In a repeat of the test with the child dummy and maximum seat pitch, the contact between the head of the adult dummy and the child dummy was minimal and the forward motion of the child dummy continued over the forward seat-back. Tether ropes eventually restrained the motion of the child dummy.

Sketches showing the kinematics of the 3 year child dummy during a test are shown by Figure 10, whilst accelerations measured at the head of this dummy are shown in Figure 11. The peak acceleration occurred when the head struck the forward seat-back.

From these tests it was clear that an unrestrained lap held infant or young child was likely to be at risk of sustaining injuries in an impact situation. Had the adult dummy been positioned to clasp the infant or child dummy this observation would still be valid. Tests conducted elsewhere [Ref 1] to explore the ability of male and female adults to restrain infant dummies have shown that, at a peak deceleration of 10g, the inertial forces of an 8kg infant and the forearms of the adult could be in excess of 1000N (225lbf). This force was considered to be beyond the strength limit for many adult females. If the child weighed more or the peak deceleration was higher, the forces would be correspondingly greater.

### 3.4.3 *Tests with Braced Unrestrained Lap Held Dummies*

In the tests where the dummies had been given initially braced postures but were unrestrained, the infant and child dummies again moved forward on the lap of the adult dummy as the trolley decelerated. The feet and head of the infant dummy first contacted the forward seat-back. The proximity of the head and chest of the adult dummy then acted to limit the motion of the infant dummy so that it sprawled over the forward seat-back. However, in the case of the child dummy, the head was initially in contact with the forward seat-back and the forward motion of the child dummy helped to push it forward. The knees of the child dummy then contacted the seat-back. The proximity of the adult dummy again controlled the motion of the child dummy, so that it also sprawled over the seat-back. Subsequently, the trajectories of the infant and child dummies were uncontrolled.

The flailing of the dummies was dramatically reduced during the tests when the dummies had been given initially braced postures, compared to the tests when the dummies had initially upright postures. Thus, the accelerations of the head of the child dummy were much lower, Figure 12.

From these tests, it was clear that even with initially braced postures, the head and torso of the infant dummy and child dummy struck the forward seat-back. Indeed, the proximity of the adult dummy, though preventing the infant or child dummy from becoming loose, actually directed them into the interaction with the seat-back. Whilst little is known about the impact tolerances of children compared to the adult male [Ref 2], head impact and thoracic injuries are the major causes of impact fatalities and serious injuries.

The forces imposed on the infant and child dummies by the adult dummy, though not measured during these tests, cannot be dismissed. Since, in the same manner that an adult cannot hold a child during an impact, neither can an adult be expected to control the movement of its own body.

### 3.4.4 *Tests with Upright Supplementary Belted Lap Held Dummies*

In the tests where the dummies had initially upright postures but were restrained by wearing a supplementary belt, the infant and child dummies moved forward on the lap of the adult dummy as the trolley decelerated, until the slack in the attachment of the supplementary belt to the adult lap belt was taken up. In the smaller seat pitch configuration, the feet of the infant dummy and the knees of the child dummy contacted the forward seat back as it rotated. Both dummies then rotated forward from the hips, over the supplementary belts. Meanwhile, the adult dummy moved forward on the seat, its knees contacted the forward seat back and then, as the lap belt tightened, its torso rotated forward from the hips over the lap belt. The head of the child dummy finally contacted the forward seat back and was immediately struck by the head of the adult dummy. The body and legs of the child dummy were caught in a scissoring action between the torso and legs of the adult dummy.

The head of the infant dummy may have contacted the forward seat back. From the cine film of the test it appeared as if the adult dummy totally enveloped the infant dummy, probably trapping it in a scissoring action much like the child dummy. Subsequently, the trajectories of the infant and child dummies were controlled by the supplementary belts so that they remained with the adult dummy.

In the larger seat pitch configuration, the knees of the adult dummy did not contact the forward seat back; instead the feet slid forward and the legs straightened. The feet of the child dummy contacted the forward seat back. The infant and child dummies both rotated forward from the hips, over the supplementary belts and their heads struck their legs. The adult dummy rotated forward from the hips, trapping the infant and child dummies between its legs and torso. The head/neck region of the infant dummy was then struck by the head of the adult dummy. Whilst in the case of the child dummy, its neck and upper back were struck by the head of the adult dummy. Again, the subsequent trajectories of the infant and child dummies were controlled by the supplementary belts.

Sketches showing the kinematics of the 3 year child dummy during a test at the larger seat pitch are shown by Figure 13. The accelerations measured at the head and chest of this dummy are shown in Figure 14 and 15. The peak head acceleration occurred when the head of the dummy struck its own legs. The peak chest acceleration occurred when the head of the adult dummy struck the neck/upper back region of the child dummy.

### 3.4.5 *Tests with Braced Supplementary Belted Lap Held Dummies*

In the tests where the dummies had initially braced postures and were restrained by a supplementary belt, the infant and child dummies were both pushed down between the legs of the adult dummy. The infant and child dummies appeared to dangle over the edge of the seat cushion held only by their supplementary belt. At one stage, almost all of the infant dummy appeared to be between or below the knees of the adult dummy. The heads of the infant and child dummies did not appear to contact their own legs and the head of the adult dummy made no contact with the infant dummy and only a minor contact with the head of the child dummy.

The very low accelerations measured at the head and chest of the child dummy clearly showed the advantage of the initially braced posture. The accelerations measured at the head of the 3 year child dummy are shown in Figure 16.

The loads imposed by the adult dummy on the infant and child dummy, though not measured, may have been lower in these tests because the infant and child dummies were pushed down between the legs of the adult dummy, rather than being crushed between its torso and legs. Nevertheless, this may have caused greater loads to be exerted by the supplementary belts on the abdomens of the infant and child dummies.

### 3.4.6 *Tests with Lap Belted Dummies*

In the tests where the dummies had initially upright postures, the kinematics of the three dummies were not dissimilar. In each case, the dummy moved forward on the seat, losing contact with the seat-back, rotated forward about the hips and then struck its own legs with its head. The greatest forward motion occurred for the 6 month infant dummy because the belt could not be tightened to provide the required slack. Consequently, the excessive slack had to be taken up before the belt was tensioned.

Sketches showing the kinematics of the 6 year child dummy during a test are shown in Figure 17 and the accelerations measured at the head of this dummy are shown in Figure 18. The peak acceleration occurred when the head struck the legs.

Of note during these tests were the straight legs of each dummy when sat on the seat – even for the 6 year child dummy. This is not a comfortable seating position for a long period of time.

The kinematics of the two child dummies were similar in the tests when each had been given initially braced postures. The flailing of the dummies was virtually absent when compared to the tests where the dummies had initially upright postures. The contact between the head and legs of each dummy was thus relatively minor, as indicated by the accelerations measured at the heads of the dummies. The accelerations measured at the head of the 6 year child dummy are shown in Figure 19.

During the test with the infant dummy in an initially braced posture, the cords that held the dummy in the braced posture broke and the test was not repeated.

During all these tests, the restraint provided by the lap belt limited the forward motion of each dummy and prevented major contact between the dummy and the forward seat-back. However, the lap belt concentrated the restraining forces on the pelvis and abdomen regions of the dummies. For infants and young children, it is desirable to avoid high, localised forces being imposed by the restraint system, because their highly cartilaginous bone structure has no firm 'anchor points'. It is better for the forces to be distributed over the whole body.

## 3.5 Major Findings

### 3.5.1 *Tests with Lap Held Dummies*

The main findings of the tests with lap held dummies on a forward facing seat can be summarised as follows:

(a) Generally:

(i) seating the infant and child dummies on the lap of the adult dummy brought them nearer to the seat back in front, increasing the likelihood of contact;

(ii) an initially braced posture was likely to reduce the severity of the impact for the infant and child dummies due to the reduced potential for the dummies to flail.

(b) With the infant or child dummies sat unrestrained on the adult dummy's lap:

(i) the infant or child dummies were likely to strike the forward seat back, even if the seat back had rotated forward through a large angle;

(ii) the head, neck or back of the infant and child dummies were likely to be struck by the head of the adult dummy;

(iii) after the initial contact with the forward seat back, the trajectories of the infant and child dummies were likely to be unpredictable.

(c) With the infant or child dummies sat on the adult dummy's lap restrained by a supplementary belt:

(i) the infant or child dummies were likely to be crushed between the legs and torso of the adult dummy and possibily pushed down between the legs;

(ii) the head or neck of the infant and child dummies were likely to be struck by the head of the adult dummy;

(iii) since the buckles of the supplementary belts lay on the abdomens of the infant and child dummies, when the dummies were doubled over (with torsos flat on legs) the buckles were pushed into the abdomen regions;

(iv) the restraining forces from the supplementary belts were concentrated on the abdomen regions of the infant and child dummies.

The following implications for live infants and young children can be deduced from the programme of tests on a forward facing seat:

(a) the carrying of infants and young children on the lap of an adult, without any recognised or approved form of restraint is likely to promote fatalities and injuries to these children during impact situations;

(b) the restraint of infants and young children by supplementary belts, whilst being carried on the lap of an adult, will eliminate the possibility of the child becoming a free flying missile in an impact situation;

(c) the restraint of infants and young children by supplementary belts, whilst being carried on the lap of an adult, may reduce the likelihood and severity of injuries due to contact with aircraft cabin furniture. However, supplementary belts may promote other injuries due to the manner in which the restraining forces will be transmitted to the children and also due to the likelihood of crushing from the adult.

On balance, it would appear that infants and young children carried on the lap of an adult without any recognised or approved form of restraint are at greater risk than those who are restrained. Nevertheless, even restrained infants and young children are at considerable risk. Generally, it would appear that lap carrying is not an optimum method for transporting infants and young children on passenger transport aircraft. Therefore, with reference to the first objective of the programme tests, in an impact situation, there is no age at which an infant or young child can be given the same protection by a supplementary belt, whilst being carried on the lap of an adult sitting on a forward facing seat, as that obtained by an adult passenger secured by a lap belt whilst sitting on a forward facing seat.

### 3.5.2 *Tests with Lap Belted Dummies*

The main findings of the tests with lap belted dummies sat on a forward facing seat can be summarised as follows:

(a) Generally:

(i) the restraining forces from the lap belt were concentrated on the pelvis and abdomen regions of the dummies;

(ii) the heads of the infant and child dummies were likely to strike the legs, forcibly if the initial posture was upright;

(iii) the back of the seat on which the infant and child dummies were sitting was likely to rotate forward and to contact the dummies; this contact was, however, considered to be of minor effect;

(iv) an initially braced posture was likely to reduce the severity of the impact for the dummies due to the reduced potential for the dummies to flail.

(b) With the 6 month infant dummy:

(i) there was likely to be insufficient adjustment for the lap belt to be tightened to a snug fit;

(ii) due to the excessive slack in the lap belt, the restraining forces (though not measured) were likely to be higher than if no slack had existed;

(iii) the restraining forces from the lap belt were imposed on the abdomen of the infant dummy due to the width of the lap belt webbing.

(c) With the 3 year child dummy:

(i) there was likely to be sufficient adjustment for the lap belt to be tightened to a snug fit;

(ii) the restraining forces from the lap belt were partially imposed on the abdomen and partially on the pelvis of the dummy due to the width of the lap belt webbing.

(d) With the 6 year child dummy:

(i) it was likely that the restraining forces from the lap belt were imposed solely on the pelvis of the dummy.

The following implications for live infants and young children can be deduced from the programme of tests on a forward facing seat:

(a) a lap belt is not an appropriate form of restraint for a 6 month old infant;

(b) a lap belt is unlikely to be the optimum form of restraint for a 3 year old child;

(c) a lap belt offers reasonable protection to a 6 year old during an impact situation, but even a child of this age would benefit from having the restraining forces more evenly distributed over their body.

On balance, it would appear that a lap belt does not provide the best protection to infants and young children. Some form of restraint with an integral harness (e.g.

automotive style child restraint) would be more appropriate. The use of such devices by children up to 3 or 4 years of age would be most beneficial. Beyond this age, a lap belt is the only form of restraint currently available for use and probably provides reasonable protection. With increasing age, the protection provided to children by a lap belt improves to that provided to adult passengers.

Therefore, with reference to the second objective of the programme of tests, the minimum age of a child who can safely be restrained by an adult lap belt lies between the ages of 3 and 6 years.

### 3.6 Conclusions from the Tests

(a) The carrying of infants and young children on the lap of an adult sitting on a forward facing seat, without any recognised or approved form of restraint, is likely to promote fatalities and injuries to these children during impact situations.

(b) Infants and young children carried on the lap of an adult sitting on a forward facing seat and secured by supplementary belts are at less risk than unrestrained infants and children.

(c) Infants and young children carried on the lap of an adult sitting on a forward facing seat and secured by supplementary belts are provided with less protection than an adult secured by a lap belt.

**Therefore, there is no age at which a young child can be given the same protection by a supplementary belt, whilst being carried on the lap of an adult sitting on a forward facing seat, as that obtained by an adult passenger secured by a lap belt whilst sitting on a forward facing seat.**

(d) A lap belt is not the most suitable form of restraint for infants and young children when sat on a forward facing seat.

(e) In the case of a forward facing seat, the protection provided to young children by a lap belt is less than that provided by a lap belt to an adult.

**Therefore, the minimum age of a child who can be safely restrained by a lap belt whilst seated in a forward facing aircraft seat lies between the ages of 3 and 6 years.**

## 4 TESTS OF ALTERNATIVE RESTRAINTS

### 4.1 Objective of the Tests

The tests of existing aviation restraints highlighted the problems and deficiencies of current restraints for securing infants and young children in aircraft. The tests indicated the need for restraints that catered for the special needs of infants and young children, due to their physical size and different bodily characteristics. Since infants and young children are not proportionally scaled down versions of adults [Ref 3], it is not possible to provide equivalent levels of safety merely by scaling down an adult restraint.

Therefore, to provide the appropriate levels of safety, it was necessary first to identify the test procedures and performance criteria against which alternate child restraint systems should be evaluated. A series of tests was then conducted to investigate whether some currently available systems (e.g. automotive child restraints) could comply with the criteria in an aviation environment. If some systems were shown to be suitable, it would then be possible to permit their use in passenger aircraft.

## 4.2 Procedures and Criteria

### 4.2.1 *Current Standards*

The standards whose test procedures and performance criteria were considered included the following:

BS 3254 part 2
BS AU202 – British standards relating to the approval of various types of infant and child restraint systems [Refs 4 and 5];

ECE Regulation 44 – European standard concerning the approval of restraint devices for child occupants of power driven vehicles ('Child Restraint Systems') [Ref 6];

FMVSS 213 – American standard which specifies the requirements for child restraint systems used in motor vehicles and aircraft [Ref 7];

JAR 25.562 – Joint Aviation Requirement applicable to the dynamic testing of seats in transport category aircraft [Ref 8].

All these standards require a dynamic test with a velocity change of around 50km/h. All except the last also require an overturning test.

### 4.2.2 *Review*

Following a review of these standards, it was concluded that:

(a) acceptance of child restraint systems by reference to automotive test criteria would probably ensure that the systems provided adequate protection for young children when used in general aviation/light aircraft, as well as in transport category aircraft;

(b) acceptance of child restraint systems by reference to European (as opposed to American) automotive test criteria, would be more appropriate – although this choice may jeopardise the possibility of achieving a world-wide standard for approving the use of child restraint systems in passenger aircraft;

(c) acceptance of child restraint systems by reference to European (as opposed to British) automotive test criteria would pave the way for a U.K. led initiative towards European acceptance of the use of child restraint systems in passenger aircraft;

(d) the test criteria of ECE Regulation 44 should be used as the reference for permitting the use of child restraint systems in passenger aircraft – with the proviso that the dynamic inversion test in the American FMVSS 213 standard should be investigated to determine whether it was a more relevant test for an aviation environment than the slow speed overturning test specified in ECE Regulation 44.

### 4.2.3 *Implications*

Many of the automotive child restraint systems manufactured in the UK meet the requirements of ECE Regulation 44 for use in automobiles. However, differences exist between the automotive and aviation environments. Two differences which have an immediate influence on safety concern the passenger seat. On an aircraft the seats need to be moveable to allow different spacings for different areas of the aircraft (i.e. first class, business class and economy). In addition, the majority of passenger seats on passenger transport aircraft have only a lap belt to secure a passenger.

In the case of children whose weight lies within the 9 to 18kg range, generally, the automotive restraints are forward facing (i.e. they face in the direction of travel). Some of these restraints provide the necessary protection even when secured solely by an automotive lap belt. However, for infants weighing less than 10kg, the automotive restraints are rearward facing. Many of these latter restraints demonstrate compliance with the ECE Regulation 44 performance criteria (and the similar excursion criteria of BS AU202) by virtue of the shoulder portion of a 3 point seat belt limiting forward rotation of the system. On an aircraft seat having only a lap belt, a rearward facing child restraint will not be secured so effectively as in the automotive environment.

Nevertheless, dynamic tests were conducted to determine whether these restraints could provide the same levels of safety in an aviation environment as in an automotive environment.

## 4.3 **Test Facilities**

### 4.3.1 *Dynamic Tests*

The tests were conducted on a HYGE (hydraulically controlled gas energised) accelerator device. Here the test item(s) and dummy(ies) were installed facing in the opposite direction from the velocity vector. Since there was no sled movement prior to the impact test pulse, the original positions/orientations of the test items or dummies were not disturbed.

The seating fixture to which the child restraints were secured was mounted on the sled of the HYGE accelerator. The fixture allowed an aircraft seat (modified to permit repeatable use) to be mounted on it, together with the back of a second seat at a location in front of the first seat.

The modified aircraft seat consisted of a single spar triple seat which had been cut down to a centre single configuration. The original legs had been removed and replaced by 12mm plate aligned longitudinally. The J-tube framework components were retained and reinforced. These tubes supported the diaphragm under the seat cushion and the seat back was located between them.

The modified seat was located behind the second seat back at a position dictated by the requirements of the CAA Airworthiness Notice No. 64 [Ref 9]. In this instance, the geometry of the seat used in the tests was such that to comply with the minimum requirements of the notice, the modified seat was located behind the second seat back at a position equivalent to a seating pitch of 838mm (33 in). This spacing was maintained for all the tests.

### 4.3.2 *Overturning/Inversion Tests*

The overturning/inversion tests were conducted on a purpose built rig at the Impact Centre. The rig was designed so that tests could be performed at different rotation speeds. This was to allow tests with rotation speeds as low as those in the range specified in ECE Regulation 44 (2 to 5 degrees/second) and at speeds as high as those in the range specified in the American FMVSS 213 (35 to 45 degrees/second).

The rig consisted of two vertical 'I' beams (bolted to a floor framework), a stepper motor and reduction gearbox mounted on top of one of the beams and two bearing blocks.

A single spar triple aircraft seat was cut down to a centre single configuration and adapted so that it could be mounted between the two vertical 'I' beams and rotated about longitudinal and lateral axes.

The location of the axes for the tests were chosen to represent those specified in the American standard due to the higher rotation speeds and hence the significance of inertial loadings. The rotation speeds in the European regulation are so slow as to make the tests quasi-static; hence the location of the axes was not critical.

The intersection of the axes in the American standard was specified as 25.4mm below the bottom of the seat frame. This location coincided reasonably well with the centre of the single spar on the aircraft seat, hence all mountings of the seat to the rig were made from the spar.

## 4.4 Test Procedures

### 4.4.1 *Dynamic Tests*

For the tests the child restraint systems were positioned and secured on the forward facing aircraft seat and the dummies positioned and secured according to the procedures in ECE Regulation 44. The recommendations of the manufacturer of each system were also taken into account - except for the rearward facing child restraints. These systems could only be secured by a lap belt (as opposed to the 3 point seat belt recommended during use in an automotive environment).

The lap belt was routed over or around each child restraint device as described in the manufacturers' instructions. No attempt was made to wrap the webbing around the metal framework of some devices or to twist the webbing so that the buckle was subsequently easier to release.

The dummies used during the tests were manufactured by the TNO Road Vehicles Research Institute in Holland and represented children of 9 months and 3 years of age. Both were instrumented with head and chest tri-axial accelerometers.

The forward facing systems were tested with both dummies, whereas the rearward facing systems were only tested with the 9 month dummy. ECE Regulation 44 calls for rearward facing systems to be tested with dummies weighing 3.4kg (new born) and 9kg. However, it was felt that the larger dummy would adequately highlight the problems of using rearward facing restraints when they were secured only by a lap belt.

The joint settings of the dummies were verified prior to each test and, where necessary, adjusted to a 1g setting.

A new child restraint system and a new lap belt were used for each test. Where possible, each lap belt was marked before the test, so that stretch or sliding of the belt through the adjuster mechanisms could be measured after the test.

The friction level at which the two aircraft seat backs would begin to rotate forward was checked regularly during the programme of tests. It was set so that the static force needed to begin rotating the seat back lay within the range of 110 to 135N (25 to 30lbf) when applied at the top of the seat back.

Following each test, the spring suspension of the aircraft seat was inspected for possible damage, due to the loads imposed by the child restraint. Where necessary, springs were replaced and in cases of extreme damage, the whole assembly (springs and diaphragm) was replaced.

The seat cushion was also changed after each test. This was necessary due to the intensive test schedule which allowed insufficient time between tests for the cushion foam to recover to its normal dimensions.

For the forward facing restraint systems, the HYGE trolley was accelerated by a longitudinal pulse which lay within the range specified in ECE Regulation 44 for frontal impact.

For the rearward facing restraint systems, the HYGE trolley was accelerated by a longitudinal pulse which conformed to the requirements of the JAR 25.562, 16g predominantly longitudinal impact test. The child restraint devices were not yawed 10 degrees during these tests, unlike aircraft seats tested to these regulations. Additionally, it was the intention that the rearward facing restraints should also be tested when the HYGE trolley was accelerated by an ECE Regulation 44 frontal impact pulse. For reasons described later, these latter tests were not conducted.

High speed cine films (1000 frames/second) were taken of each test by cameras positioned to one side of and above the aircraft seat. The camera at the side was mounted on the sled whereas the camera above was stationary.

### 4.4.2 *Overturning/Inversion Tests*

Two sets of overturning/inversion tests were conducted. The first evaluated the stability of each child restraint system when it was secured to an aircraft seat and the combination, complete with dummy, was rotated at a speed within the range 2 to 5 degrees/second. The second evaluated the stability with rotation speeds at levels more relevant to an aviation environment. For this purpose, the rotation speed range specified in the American FMVSS 213 was used – 35 to 45 degrees/second.

During both sets of tests, the restraint systems and dummies were positioned and secured using the procedures described in ECE Regulation 44. The manufacturers' installation recommendations for each system were also taken into account.

Many other preparation procedure details were similar to those used for the dynamic impact tests; in particular, the securing of the rearward facing restraint systems solely by a lap belt and the testing of them only with a 9kg dummy.

The tests to the ECE Regulation 44 were performed so that the aircraft seat, child restraint and dummy were rotated through 360 degrees about a horizontal longitudinal axis, in both clockwise and counter-clockwise directions. The tests were repeated with rotations about a horizontal lateral axis. The speed of rotation during these tests was 4.5 degrees/second.

The tests with FMVSS 213 rotation speeds were performed so that the aircraft seat, child restraint and dummy were rotated forward about a horizontal lateral axis and sideways about a horizontal longitudinal axis. For each test the rotation was stopped when the combination of seat, restraint and dummy was in an inverted position. The speed of rotation during these tests was 36 degrees/second.

## 4.5 Child Restraint Systems Tested

Since ECE Regulation 44 had been selected for the test procedure and performance criteria against which systems were to be evaluated, preference was given to selecting automotive child restraint systems that were already approved against this regulation when secured solely by a lap belt. Nevertheless, some systems approved to British Standards were also selected, as was a prototype aviation-unique restraint system.

Five forward facing child restraints were selected (three approved to ECE Regulation 44, one approved to BS 3254 part 2, one aviation unique) and four rearward facing child restraints (all approved to ECE Regulation 44). One of the restraints was included in both categories. The masses of the restraints are given in Table 1.

## 4.6 Installation of the Child Restraint Systems on the Aircraft Seat

### 4.6.1 *Forward Facing Restraints*

All these restraints had a metal framework or metal components around which the lap belt was routed. Where the manufacturers' instructions explained and/or illustrated the routing for the webbing of a lap belt, the restraint systems were installed accordingly. If no clear instructions were given, an appropriate routing was devised which minimised the length of belt webbing needed.

No attempt was made to wrap the belt webbing around any part of the metal framework of each system. The belt was simply laid across the relevant frame members or components, the two halves joined at the buckle and the belt tightened as recommended in the manufacturers' instructions. The buckle of the lap belt lay close to, or against the framework of some of the systems – although this would not in itself have necessarily caused the lap belts to function in an adverse manner. In one particular case, the position of the belt buckle did cause concern, but during the tests with this system the belt functioned normally.

There was some variation in the initial positions of each restraint system between the tests with the 9kg and 15kg dummies. In the main, this was accounted for by the greater weight of the larger dummy pushing the restraints further down into the aircraft seat cushion. In some cases, the greater weight caused the rear support of the system to slip down the gap between the back of the seat cushion and the lower edge of the seat back.

### 4.6.2 *Rearward Facing Restraints*

Three of these systems were of non-metallic construction, whilst one had a metal framework. None of the manufacturers' instructions described and/or illustrated use of the systems with only a lap belt to secure it in position. Consequently, the sole use of a lap belt to secure these systems to the aircraft seat must be considered as a *non-standard installation*.

The three systems of non-metallic construction were secured by laying the lap belt over the top of the system and locating the webbing under lugs, or in depressions, on the sides of the system – the recommended routing for the lap section of a 3 point automotive seat belt. The system with a metal framework was secured in position by routing the lap belt around the framework in the manner indicated for the lap section of a 3 point automotive seat belt The latter system required a much shorter length of lap belt webbing to secure it in position.

The base of one of the systems projected beyond the front edge of the seat cushion, whilst the bases of the other systems lay behind the front edge by varying amounts.

## 4.7 **Results**

### 4.7.1 *Velocity Change and Acceleration Achieved*

The average velocity change of the sled during the dynamic tests with the forward facing restraints was 48.3km/h and a typical acceleration pulse is shown in Fig 20. The average velocity change of the sled during the tests with the rearward facing restraints was 53.1km/h and a typical acceleration pulse is shown in Fig 21. The results from all the tests with the forward facing restraints are summarised in Tables 2 and 3 and in Tables 4 and 5 for the tests with rearward facing restraints. Note: the accelerations measured at the head and chest of each dummy during these tests are not comparable with those measured during the tests described in Section 3 of this report due to the difference in the sled pulses.

### 4.7.2 *Tests with Forward Facing Child Restraints*

Those child restraints with a metal framework imposed concentrated loadings on the seat cushion during the tests, since the front and rear supports were part of the framework. Nevertheless, all but one of the restraints remained stable on the aircraft seat during the tests. One restraint was not stable since the front support slipped off the front edge of the seat cushion.

Two child restraints imposed such high loadings on the seat cushion and suspension arrangements underneath, that the latter had to be completely replaced. The child restraint which slipped off the front of the seat cushion was one of these.

The geometry of the pelvis and crotch straps of one of the child restraints was such that they might promote submarining under the pelvis straps. Thus forces were not applied solely to the pelvis of the dummy but also to the abdomen.

Only one of the child restraints performed in a manner so that all the ECE Regulation 44 criteria were met during the tests with the smaller 9kg dummy. Two met the head excursion criteria and one of the acceleration criteria, but failed to meet the resultant chest acceleration criterion. Two failed to meet the horizontal head excursion criterion, but perhaps as a consequence, met both the chest acceleration criteria.

During the tests with the 3 year (15kg) dummy again, only one of the child restraints performed in a manner so that all the criteria were met. However, it was not the same restraint that had met all the criteria during the tests with the 9 month (9kg) dummy. Three failed to meet the horizontal head excursion criterion but perhaps as a consequence, met the chest acceleration criteria. One met the head excursion criteria, but failed to meet the resultant chest acceleration criterion.

During all these tests, the worst acceleration value measured was 27% in excess of the criterion, others were 9% or less in excess. Similarly, the worst horizontal head excursion value measured was 32% in excess of the criterion, whilst the least in excess was still 14% in excess of the criterion.

The forward rotation of the seat back against the back of the child restraints may have aggravated the performance of some of the child restraints. Consequently, during the tests with the child restraints sat on an aircraft seat, the restraints had an inertia loading applied to them from the back of the aircraft seat.

### 4.7.3 *Tests with Rearward Facing Child Restraints*

One of the restraints of non-metallic construction suffered such gross distortion during the test that it was not considered to have performed in an acceptable manner nor to have provided the same protection as it would in an automotive environment. The reasons for this situation were almost certainly associated with the non-standard installation where the restraint was secured solely by a lap belt.

The performance of the other two restraints of non-metallic construction, where the lap belt was routed over the top of the restraints, also suffered due to the non-standard installation. In these cases, the sides of the restraints were squeezed towards each other causing permanent deformation and allowing the restraint to slide forward on the aircraft seat. The front edge of the seat cushion and underlying suspension were then compressed causing each restraint to pitch downward over the edge of the cushion.

The performance of the restraint with a metal framework also suffered due to the non-standard installation. In this case the framework did suffer minor permanent deformation (but not fracture of any part), however, the restraint moved forward on the seat very little. Instead, the combined weight of the restraint and dummy pushed the support furthest from the rear of the seat cushion, down into the cushion. Most of the movement of the dummy's head was thus due to the restraint rotating about this support/seat cushion contact point.

Therefore, none of the child restraints was sufficiently constrained by the lap belt to prevent the horizontal head excursions of the dummy from exceeding the ECE Regulation 44 criterion. The vertical head excursions of the dummy were below the criterion. The accelerations measured at the chest of the dummies were below the criteria for each of the restraints. In addition, the accelerations measured at the head of the dummies were relatively low – however there are no head acceleration criteria in ECE Regulation 44.

The forward rotation of the back of the aircraft seat may have aggravated the performance of these child restraints. As in the case of the forward facing restraints, the test seat described in ECE Regulation 44 has a fixed seat back.

The forward seat back also rotated forward during each test, thus providing no support for the child restraints. With the seat pitch used in these tests, 838mm (33 in), the rearmost point of this seat back (in the upright position) was within 2mm of the forward head excursion limit. Therefore, in this instance, the forward seat back would need to remain almost in its initial upright position if it were to provide any support to a restraint and so prevent the excursion of the head of the dummy from exceeding the specified limit. However, the consequences of a restraint striking the forward seat back would then need to be evaluated.

On the basis of results from the tests when the sled had a 16g aviation pulse, further tests with a sled pulse as defined in ECE Regulation 44 for frontal impact were not conducted.

4.7.4 *Overturning/Inversion Tests*

Almost 80 individual tests were needed to check all the child restraints in all the configurations and at both rotation speeds.

During tests to the ECE 44 specification, not one of the restraint systems failed to meet the required performance criteria, even though the rearward facing systems were only secured with a lap belt. That is; in each case the test dummy did not fall out of the system and when the system was inverted, the head of the dummy had not moved more than 300mm vertically from its original position. In all cases, the movement of the head of the dummy was substantially less than 300mm. In most cases, the head of the dummy did not project beyond the top of the seat back (i.e. top of the head-rest).

For tests with rotation speeds in the range specified in FMVSS 213, the performance criteria of that standard were used. However, not one of the restraint systems failed to meet these criteria, since in each case, the restraint did not fall out of the adult lap belt, nor did the dummy fall out of the restraint during the rotation or during the three second period following the halting of rotation at the inverted position.

The following points, arising from the tests, are worth noting:

(a) the arms of the aircraft seat limited the sideways motion of the restraint systems during rotations about a horizontal longitudinal axis;

(b) the rearward facing restraints moved about on the aircraft seat more than the forward facing restraints to the extent that some did not return to the initial position after the 360 degrees rotation in the ECE Regulation 44 procedure.

## 4.8 Discussion

### 4.8.1 *Forward Facing Child Restraints*

On the basis of the results from the tests with these restraints, it would appear that the suspension characteristics of the aircraft seat were different from those of the test seat used for the approval of restraints to ECE Regulation 44. Conversely, it could be questioned whether the characteristics of current automobile seats were the same as the test seat used for the approval of restraints to ECE Regulation 44. Therefore, it might be expected that the current test results showed variations from those achieved during an automotive approval test.

Nevertheless of greatest concern was the fact that three of the restraints caused either or both of the dummies (9kg and 15kg) to undergo large forward excursions. In an aircraft, this might expose children to the risk of striking some unyielding part of the rear of a seat.

Whilst the sled pulse for the tests was more severe than would reasonably be expected during a crash of a transport category aircraft, it might not be so inappropriate for a crash of a general aviation/light aircraft. For the four child restraints which remained stable on the aircraft seat, it is feasible to conclude that with a less severe sled pulse the head excursions would drop even further and the resultant chest accelerations would drop to or below the ECE Regulation 44 criterion. For the one restraint which was not stable, it is more difficult to predict how it might perform with a less severe sled pulse. If the front support remained on the seat cushion, the accelerations measured in a dummy might increase.

Therefore, it would be feasible for the CAA to permit the use of forward facing restraints on the basis of their performance in an automotive impact test, when they were secured solely by a static lap belt. On this basis they offered greater protection to a child occupant than could be provided by other means e.g. supplementary belt or lap belt.

### 4.8.2 *Rearward Facing Child Restraints*

As a consequence of these tests, it is unlikely that any current rearward facing child restraint could meet the dynamic test criteria of ECE Regulation 44 when secured to an aircraft seat solely by a lap belt, even when the sled pulse had a 16g aviation characteristic.

Having the back of the restraint up against the forward seat back might offer some advantages, but if the forward seat back had an unlimited forward rotation capability the advantage would be lost.

Consequently, using the criteria set before the test programme, it will be impossible for the CAA to permit the use of any rearward facing child restraint on a forward facing aircraft seat. Current restraints need the support provided by the shoulder portion of a 3 point automotive style seat belt to limit forward excursion.

### 4.9 Conclusions From The Tests

#### 4.9.1 *Forward Facing Child Restraints*

(a) When tested on a single spar aircraft seat most of the selected restraints did not perform as well as during their automotive approval tests when on a standard test seat.

(b) During an aircraft crash, with lower decelerations than those used for the dynamic tests, the performance of the selected child restraints would improve, thus providing protection nearer to that expected in an automotive environment.

(c) It would be feasible for the CAA to permit the use of forward facing child restraints in an aviation environment on the basis of their performance in an automotive impact test, when secured solely by a lap belt. This is on the assumption that the decelerations involved in aviation crashes are generally less severe than those in automotive crashes.

(d) The protection provided by forward facing child restraints was superior to that provided by other devices, e.g. supplementary belts and lap belts.

#### 4.9.2 *Rearward Facing Child Restraints*

(a) When tested on a single spar aircraft seat and secured solely by a lap belt, none of the selected rearward facing child restraints were able to demonstrate levels of performance similar to those expected in an automotive environment, despite the use of a sled pulse having a 16g aviation characteristic.

(b) The use solely of a lap belt to secure the rearward facing restraints to the aircraft seat was probably the main reason for the degraded performance of these restraints.

(c) It will be impossible for the CAA to permit the use of rearward facing child restraints secured solely by a lap belt on a forward facing aircraft seat using the performance criteria selected prior to the test programme.

#### 4.9.3 *Overturning/Inversion Test Procedures*

(a) On the basis of the current tests, the inversion test specified in the American FMVSS 213 regulation is no more discerning than a slow speed rotation test at evaluating the dynamic overturning stability of current U.K. child restraints.

## 5 ACHIEVING IMPROVED PROTECTION FOR INFANTS

In the previous phase of work it was found to be impossible to make any recommendations concerning the acceptance of rearward facing child restraints for use on forward facing aircraft seats. The non-standard restraint of the systems solely by a lap belt was identified as the major reason for this situation (in the automotive environment a 3 point seat belt – lap and diagonal sections – would be used to restrain the motion of a child restraint system). It would not be impossible to design and build an aircraft seat that could be fitted either with a three point seat belt or a four point harness. However, the seat would be heavier to withstand the greater forces imposed on it by the belt system or harness. It might also be necessary for a seat of this type to have a seat back locked in the upright position.

In the previous tests initial forward motion was characterised by translation in a forward direction and/or rotation about a horizontal lateral axis. During the previous tests with the rearward facing restraints of non-metallic construction, the initial motion was characterised by substantial forward translation and some rotation. Whilst the initial motion of the restraint with a metal framework was characterised by little forward translation and substantial rotation.

Consequently, some form of restraint to control both of these motions would be required. Using combinations of belts attached to the anchorages of current aircraft passenger seats, it would be very difficult if not impossible to achieve this. Certainly, a lap belt on its own would not provide the control. Yet additional belts would constitute a non-standard fitment, unique to securing a rearward facing child restraint. In any case, additional belts would need to be longer than current lap belts in order to allow the belt to be routed around the front of a restraint. To achieve the restraint necessary for a rearward facing restraint to comply with the criteria used during the test programme, an anchorage at a location above the current lap belt anchorages would be needed. Another anchorage on the back of a current seat would provide no benefit if the seat back rotated forward during an impact. A seat with a locked back might be suitable provided any additional belt needed to secure the child restraint could be positively located on the seat back. However, such seats are not common, except in seat rows adjacent to emergency exits. The CAA currently directs that child restraints shall not be located on seats in these rows. The necessary restraint could be achieved by having an anchorage on a bulkhead behind a seat or on the side wall of the cabin, although this would clearly limit the seating positions that could be used for infants in child restraints.

One other alternative would be for a child restraint to be located on a seat where the seat in front had a locked seat back and the seat pitch was small enough that the child restraint was initially in contact with this seat back. Given the range of initial clearances during the tests of rearward facing child restraints (40 to 80mm), it would be necessary for an aircraft operator to know exactly which child restraints were to be used for a particular flight and rearrange the cabin interior accordingly. The practical difficulties make this alternative unworkable.

A different approach to this problem would be to use rearward facing aircraft seating in conjunction with a child restraint facing in the same direction as the aircraft seat. The aircraft seat would then support the child restraint and occupant and the deceleration forces during an impact would be distributed over the whole body of the occupant. This approach would also work exceedingly well for older children in a child restraint facing in the same direction as a rearward facing seat.

In the future some of these approaches may be feasible. At present achieving improved protection for infants in aircraft will need to be accomplished by utilising existing cabin equipment in conjunction with child restraints.

Therefore, the previous test results were re-examined to determine whether the failure of the rearward facing restraints to meet the criteria set prior to the tests should preclude their use in aircraft, if they provided greater protection than that currently available for infants. The results from the restraint that performed in an unacceptable manner were not considered here.

During the tests with the rearward facing restraints, the seat spacing was as dictated by the minimum requirements of Airworthiness Notice No. 64 – giving rise to a pitch of 838mm (33 in). With this seat pitch the ECE Regulation 44 forward excursion limit (550mm from intersection of seat back and seat base cushion) was within a few millimetres of the vertical projection of the rearmost point on the forward seat back. As the HYGE sled accelerated during each test the forward seat back rotated forward and at no stage did any of the restraints contact the forward seat back. Given the initial clearances between the restraints and the forward seat back, it is likely that if a seat pitch of 787mm (31 in) could be achieved and the requirements of Airworthiness Notice No. 64 were met, the restraints would still probably not contact the forward seat back as it rotated. Below a seat pitch of 787mm (31 in), the tested child restraints would not fit on the seat and between the two seat backs i.e. between the seat back of the seat that the restraint was sat on and the rear of the forward seat back.

It would be preferable to use the same forward excursion limit for rearward facing restraints as for forward facing restraints and also to offer the same protection in aircraft as in automobiles. However, whilst this was not achievable with the rearward facing restraints that were tested, the protection offered to an infant in such a restraint would not be unduly compromised, since during the tests, the other criteria were met and there was no contact with the forward seat.

Thus, it would be feasible for the CAA to permit the use of rearward facing child restraints secured solely by a lap belt on a forward facing aircraft seat, on the basis of a sled test with a 16g longitudinal triangular pulse (as specified in JAR 25.562 [Ref 8]), as long as the dummy acceleration criteria were met and there was no contact with a forward seat or other obstruction.

The General Exemption to Air Navigation Order 1989 specifically states that a child restraint 'shall not be located in a row of seats which is either adjacent to an emergency exit or is immediately forward or aft of such a row'. However, it is only seats in rows immediately forward and aft of Type III and Type IV emergency exits (located in mid-cabin) that are required to have seat backs with restricted recline and break forward [Ref 10]. Therefore, child restraints are unlikely to be located on seats where the seat in front has either a locked seat back or a seat back with a restricted break-forward capability. Consequently, the situation where a rearward facing child restraint might strike the forward seat back due to its limited break-forward capability is not likely to arise. If seats with restricted seat back rotation become standard fitment in aircraft cabins at all locations, further research will need to be conducted to evaluate the severity of any contact between a rearward facing child restraint and the seat back and the consequences for an infant occupying the restraint.

## 6 SUMMARY OF CONCLUSIONS

(a) The carrying of infants and young children on the lap of an adult sitting on a forward facing seat, without any recognised or approved form of restraint, is likely to promote fatalities and injuries to these children during impact situations.

(b) There is no age at which a young child can be given the same protection by a supplementary belt, whilst carried on the lap of an adult sitting on a forward facing seat, as that obtained by an adult passenger restrained by a lap belt whilst sitting on a forward facing seat.

(c) The minimum age of a child who can be safely restrained by a lap belt whilst seated in a forward facing aircraft seat lies between the ages of 3 and 6 years.

(d) It would be feasible for the CAA to permit the use of forward facing child restraints in an aviation environment on the basis of their performance in an automotive impact test when secured solely by lap belt. This is on the assumption that the decelerations involved in aviation crashes are generally less severe than those in automotive crashes.

(e) The protection provided by forward facing child restraints was superior to that provided by other devices, e.g. supplementary belts and lap belts.

(f) It will be impossible for the CAA to permit the use of rearward facing child restraints secured solely by a lap belt on a forward facing aircraft seat *using the performance criteria selected prior to the test programme.*

(g) It would be feasible for the CAA to permit the use of rearward facing child restraints secured solely by a lap belt on a forward facing aircraft seat, on the basis of a sled test with a 16g longitudinal triangular pulse (as specified in JAR 25.562), as long as the dummy acceleration criteria were met and there was no contact with a forward seat or other obstruction.

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**Table 1 Masses of child restraint systems**

| *Child Restraint* | *Mass (kg)* |
|---|---|
| A | 5.66 |
| B | 5.25 |
| C | 6.28 |
| D | 5.75 |
| E | 5.65 |
| F | 2.02 |
| G | 0.82 |
| H | 2.58 |

**Table 2 Initial position and movement of forward facing child restraints and dummy**

| Restraint system | Dummy mass (kg) | Max length of system (mm) | Initial distance from edge of seat to base/front bar of system (mm) | Slip of aircraft lap belt (mm) | Slip of harness straps (mm) | | | | | Position of dummy's head WRT $C_r$ point (mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Left shoulder | Right shoulder | Left pelvis | Right pelvis | Crotch | Most forward | Most upward |
| A | 9 | 380 | 110 | 0 | 7 | 8 | 6 | 5 | 0* | 523 | 655 |
| B | 9 | 510 | 150 | 0 | 0 | 1 | 0 | 0 | 0 | 643 | 624 |
| C | 9 | 415 | 55 | 7 | 1 | 1 | 1 | 1 | 1 | 630 | 561 |
| D | 9 | 470 | 70 | + | + | + | + | + | 0* | 536 | 535 |
| E | 9 | 390 | 95 | 0 | 5 | 2 | 0 | 0 | 0* | 498 | 643 |
| A | 15 | 380 | 110 | 0 | 6 | 3 | 3 | 2 | 0* | 529 | 693 |
| B | 15 | 510 | 165 | 2 | 0 | 0 | 0 | 0 | + | 725 | 655 |
| C | 15 | 415 | 70 | 8 | 0 | 0 | 0 | 0 | 0 | 649 | 611 |
| D | 15 | 470 | 70 | 0 | 10 | 7 | 10 | 8 | 0* | 688 | 624 |
| E | 15 | 390 | 105 | 0 | 6 | 6 | 0 | 0 | 0* | 535 | 725 |
| ECE Regulation 44 limits | | | | | | | | | | 550 | 800 |

Note: * Crotch strap not adjustable
+ Not measured
WRT = with respect to

**Table 3 Summary of sled and dummy instrumentation results for forward facing child restraints**

| Restraint system | Dummy mass (kg) | Peak sled accel ('g') | Sled velocity change (km/h) | Peak resultant chest accel ('g') | Peak vertical accel chest to head ('g') | Peak resultant head accel ('g') | Head injury criterion |
|---|---|---|---|---|---|---|---|
| A | 9 | 21.8 | 48.3 | 70 | 30 | 87 | 1080 |
| B | 9 | 22.0 | 48.5 | 38 | 14 | 66 | 500 |
| C | 9 | 22.4 | 48.5 | 48 | 19 | 68 | 420 |
| D | 9 | 22.4 | 48.3 | 39 | 19 | 57 | 660 |
| E | 9 | 22.4 | 48.0 | 59 | 14 | 71 | 540 |
| A | 15 | 22.1 | 48.2 | 60 | 19 | 129 | 1360 |
| B | 15 | 22.0 | 48.3 | 32 | 19 | 67 | 830 |
| C | 15 | 22.4 | 48.1 | 44 | 19 | 73 | 770 |
| D | 15 | 21.8 | 48.4 | 54 | 5 | 82 | 890 |
| E | 15 | 22.6 | 48.4 | 54 | 27 | 100 | 980 |
| ECE Regulation 44 limits | | | | 55 | 30 | | |

Note: Accel = acceleration

**Table 4 Initial position and movement of rearward facing restraint systems and dummy**

| *Restraint system* | *Dummy mass (kg)* | *Max length of system (Dim A, Fig 22) (mm)* | *Initial clearance with forward seatback (Dim B, Fig 22) (mm)* | *Initial distance from edge of seat to base of system (Dim C, Fig 22) (mm)* | *Crush of seat sides (mm)* | *Slip of aircraft lap belt (mm)* | *Position of dummy's head WRT $C_r$ point (mm)* | | *Estimated minimum back angle˚ (Angle X, Fig 22)* |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | *Most forward* | *Most upward* | |
| E | 9 | 550 | 40 | 120 | 25* | 2 | 731 | 486 | 30 |
| F | 9 | 540 | 80 | 35 | 111 | 8 | 806 | 640 | 32 |
| G | 9 | 610 | 30 | 80 | – | – | 1016 | 438 | – |
| H | 9 | 585 | 60 | –45 | 16 | 7 | 756 | 611 | 26 |
| ECE Regulation 44 limits | | | | | | | 550 | 800 | |

Note: * Lap belt guide on right hand side bent this far at top
˚ Angle between the system's back support surface and the horizontal
WRT = with respect to

**Table 5 Summary of sled and dummy instrumentation results for rearward facing child restraints**

| *Restraint system* | *Dummy mass (kg)* | *Peak sled accel ('g')* | *Sled velocity change (km/h)* | *Peak resultant chest accel ('g')* | *Peak vertical accel chest to head ('g')* | *Peak resultant head accel ('g')* | *Head injury criterion* |
|---|---|---|---|---|---|---|---|
| E | 9 | 17.2 | 52.9 | 25 | 4 | 43 | 210 |
| F | 9 | 18.3 | 53.8 | 33 | 6 | 36 | 210 |
| G | 9 | 17.4 | 52.9 | 21 | 3 | 75 | 410 |
| H | 9 | 16.8 | 52.8 | 32 | 5 | 38 | 260 |
| ECE Regulation 44 limits | | | | 55 | 30 | | |

Note: Accel = acceleration

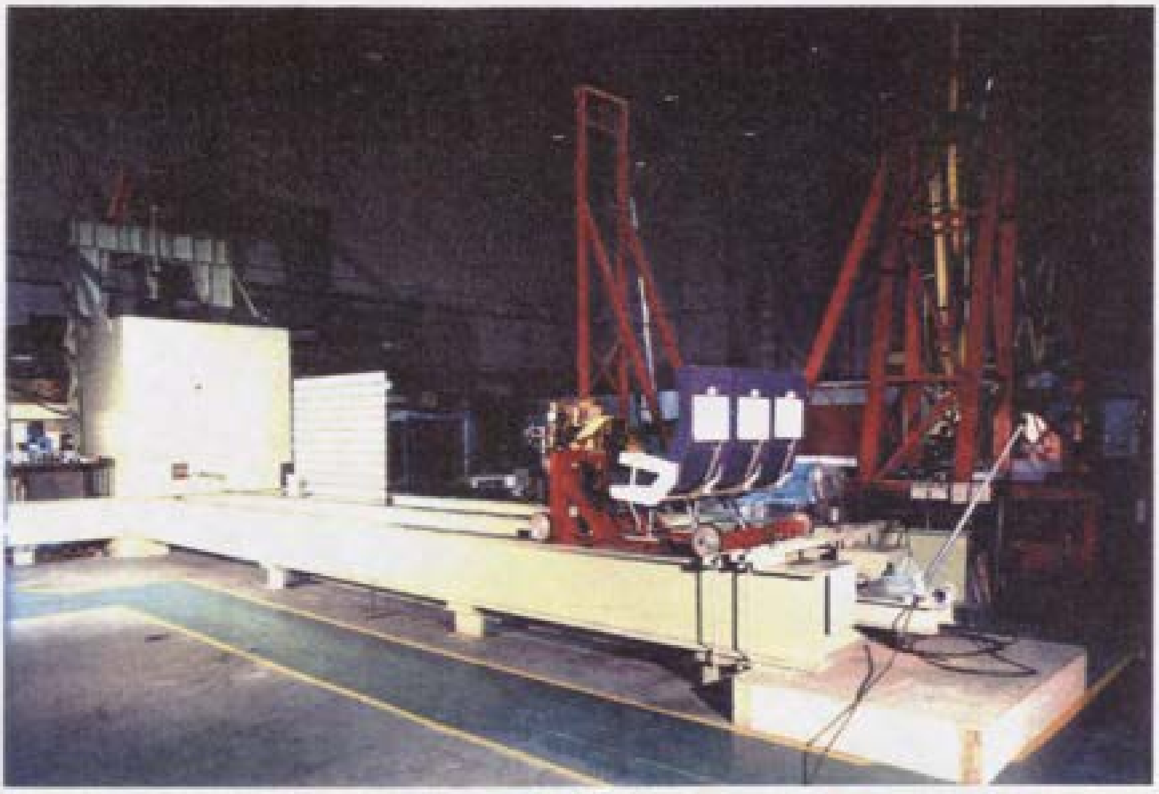

Figure 1 The Cranfield Impact Centre Aircraft Seat Dynamic Test Facility

Figure 2 The on-board data recording system

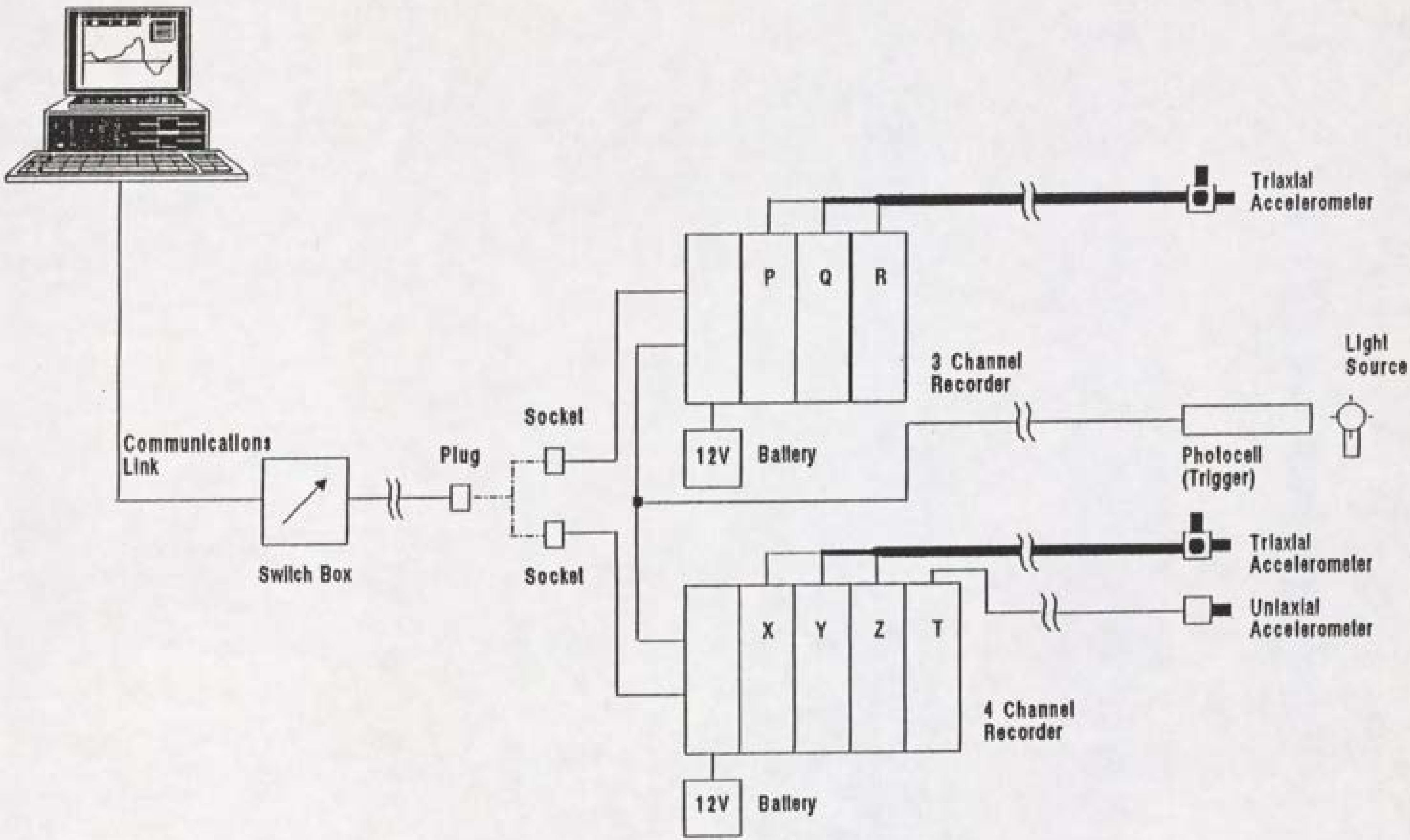


Figure 3 Block diagram of on-board data recording system and instrumentation

Figure 4 3 year child dummy restrained with a supplementary belt

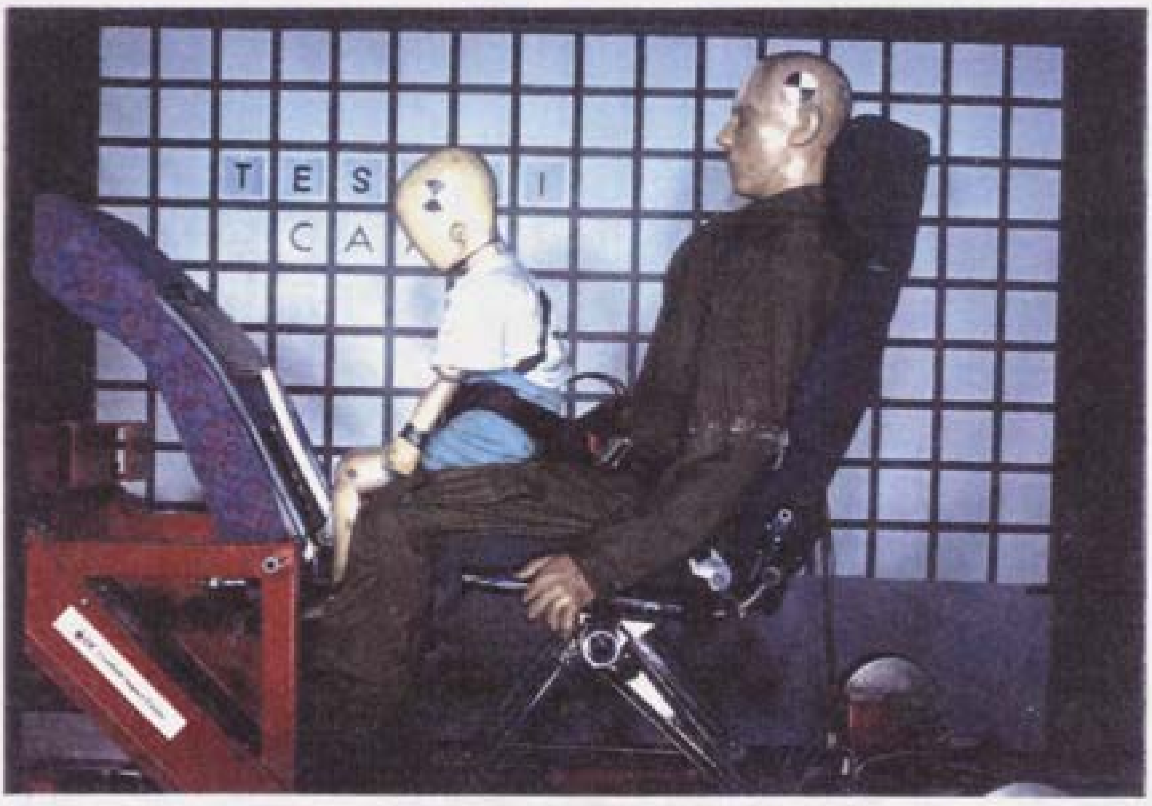

Figure 5 Forward movement allowed by attachment of supplementary belt to adult lap belt


Figure 6   6 month infant dummy restrained with a supplementary belt

Figure 7   3 year child dummy in a braced posture


Figure 8 6 year child dummy restrained with an adult lap belt

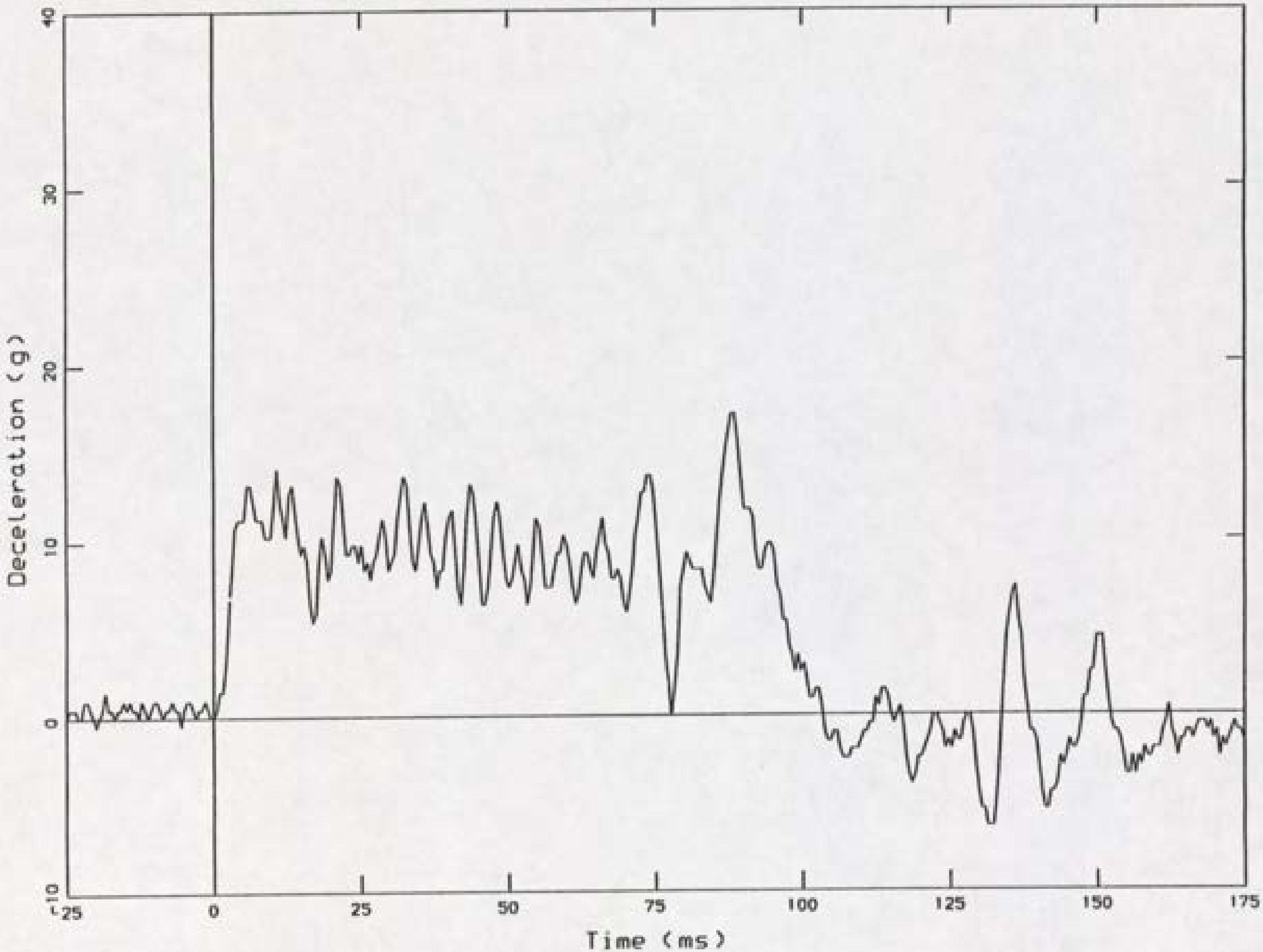


Figure 9 Typical trolley deceleration pulse


**Figure 10 Kinematics of unrestrained, lap held 3 year child dummy**

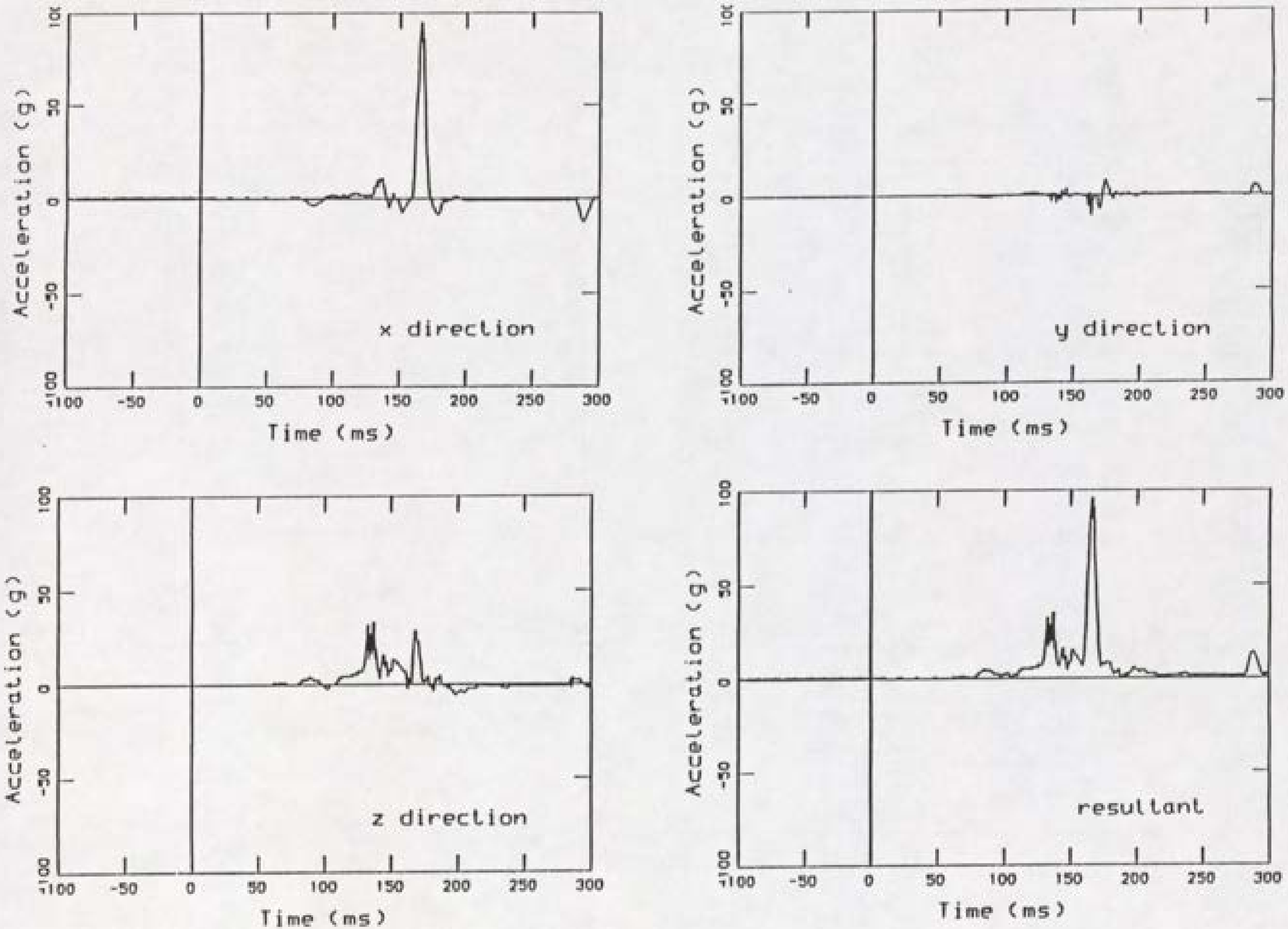


Figure 11 Head accelerations for unrestrained, lap held 3 year child dummy

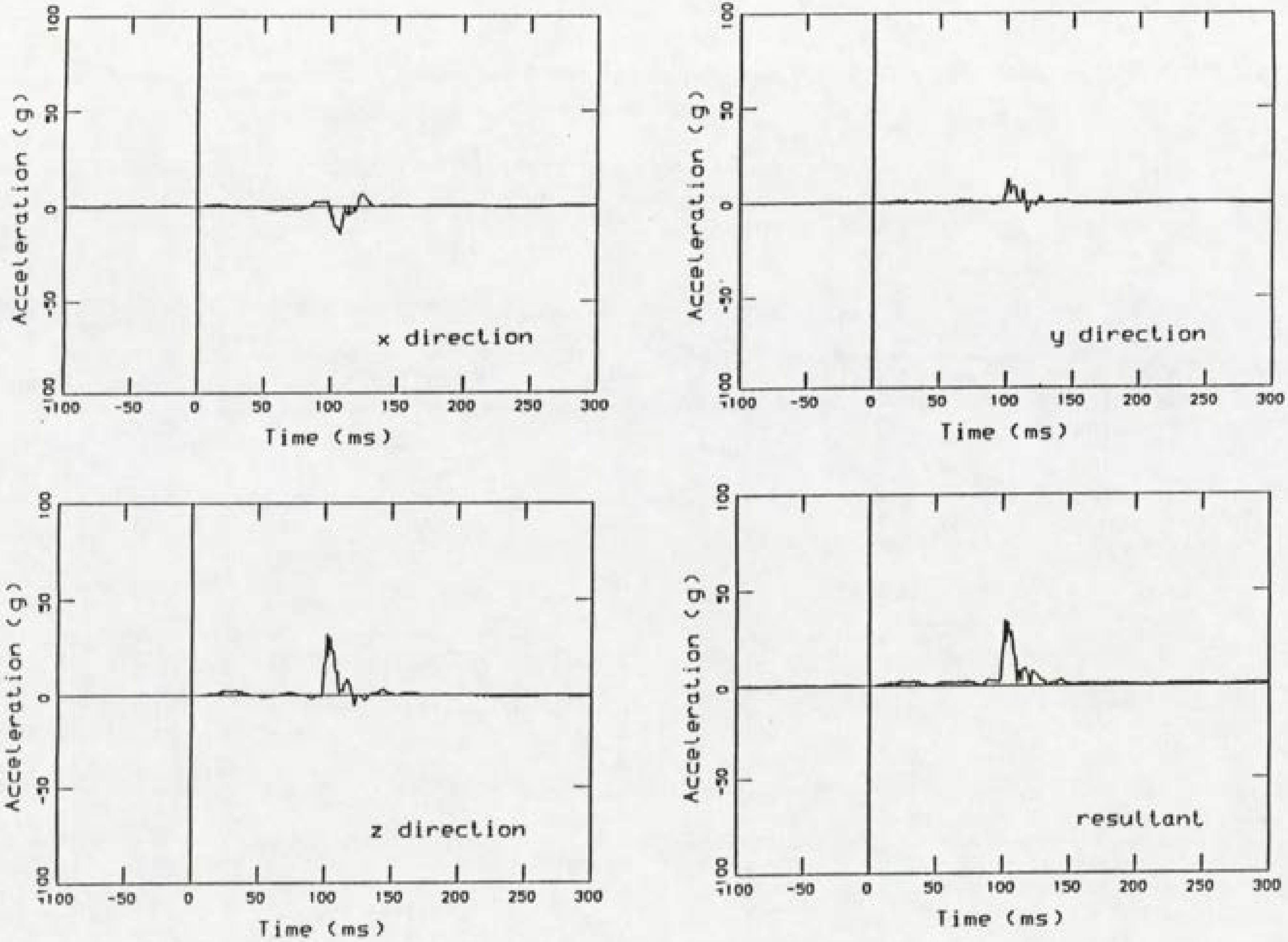

Figure 12 Head accelerations for unrestrained, lap held and braced 3 year child dummy

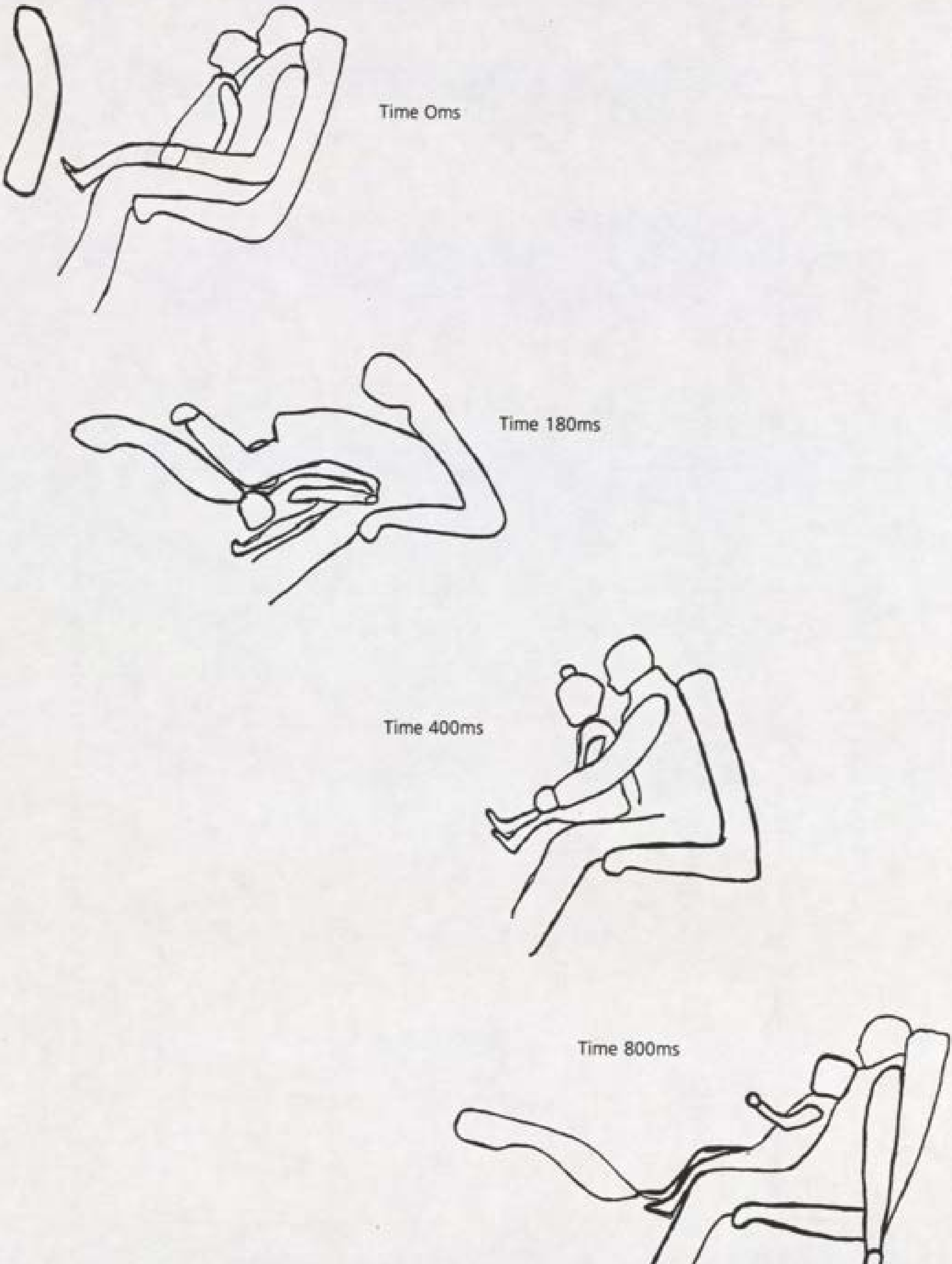


**Figure 13 Kinematics for supplementary belted 3 year child dummy**

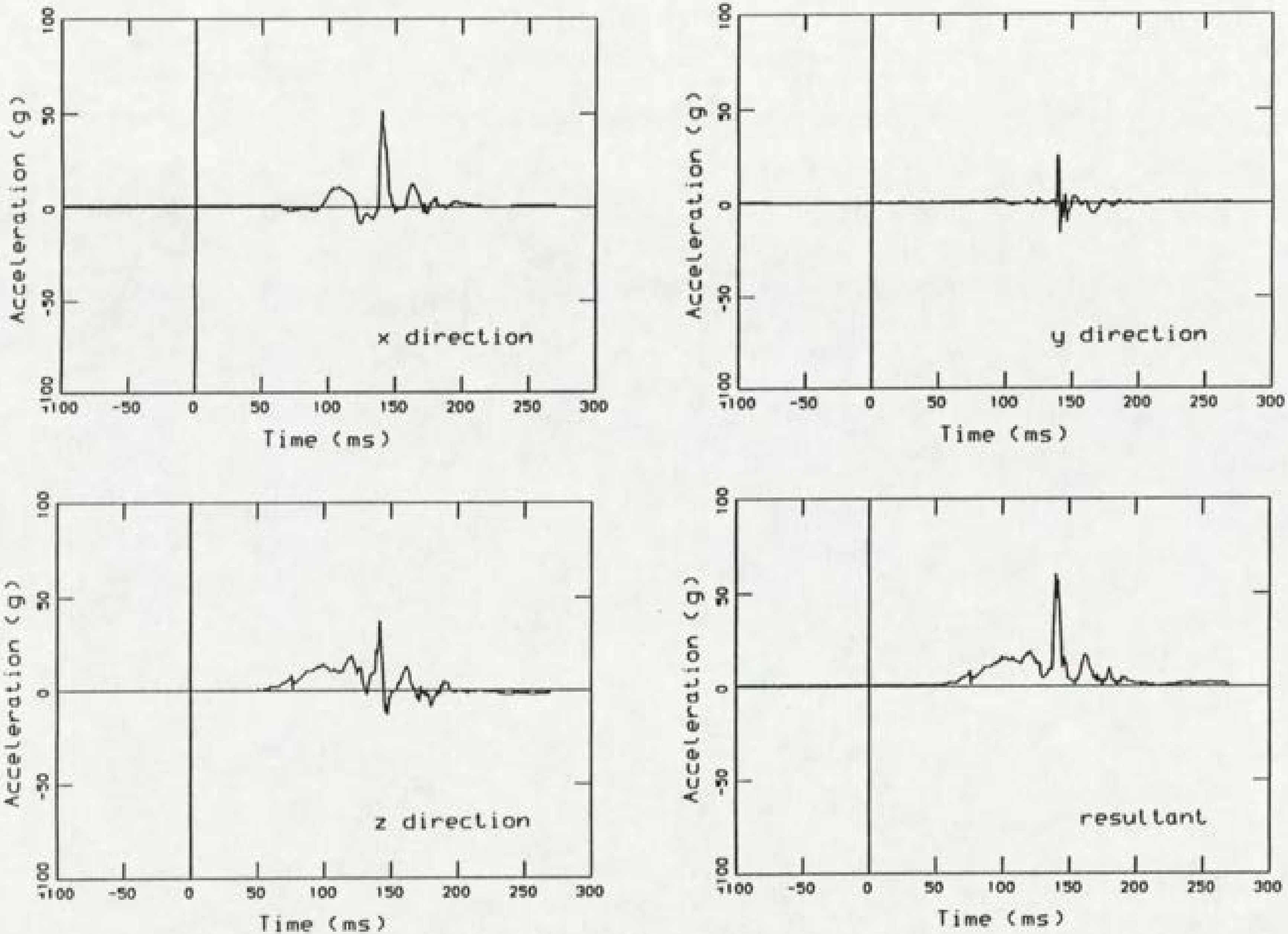


**Figure 14 Head accelerations for supplementary belted 3 year child dummy**

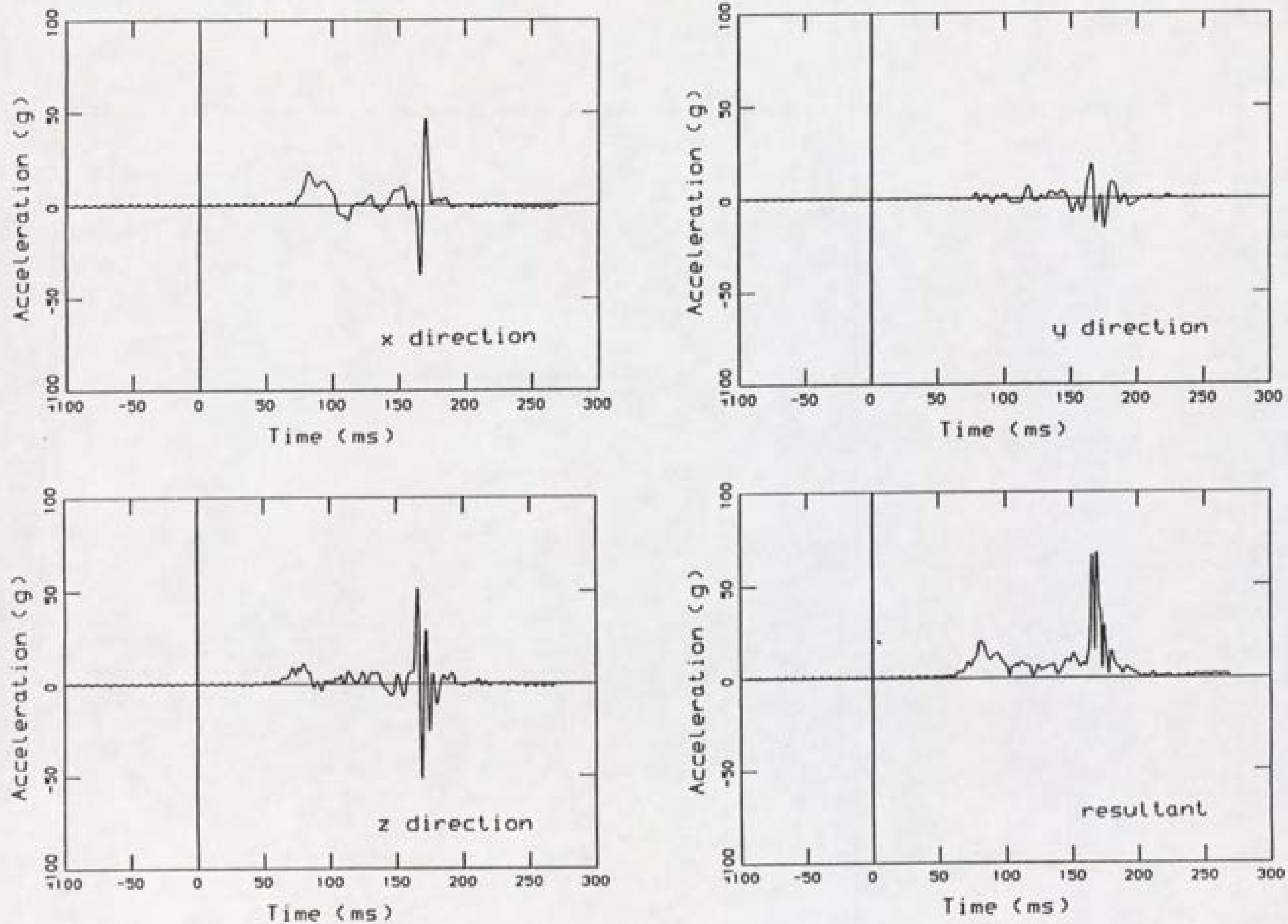


**Figure 15 Chest accelerations for supplementary belted and braced 3 year child dummy**

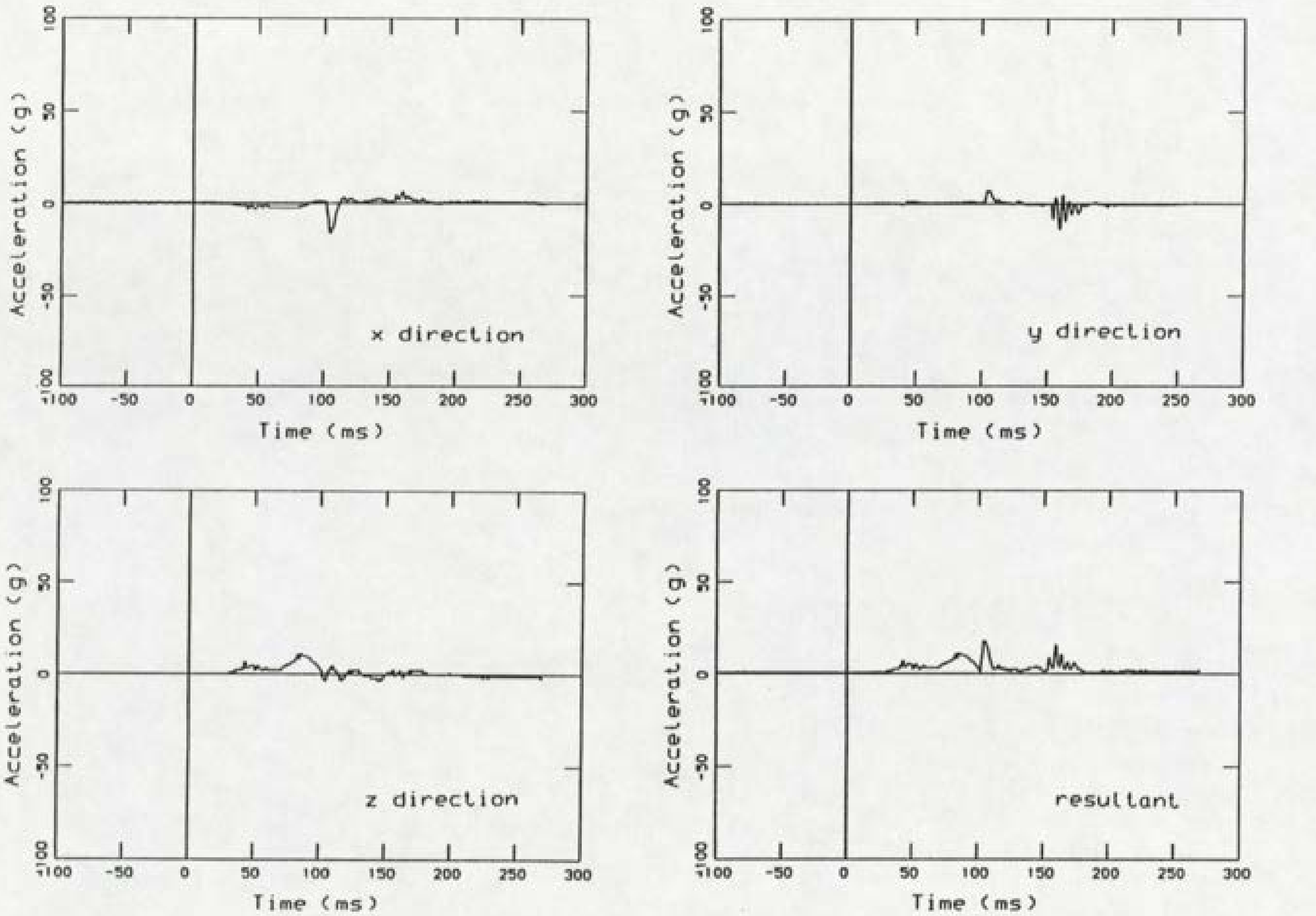


Figure 16 Head accelerations for supplementary belted and braced 3 year child dummy

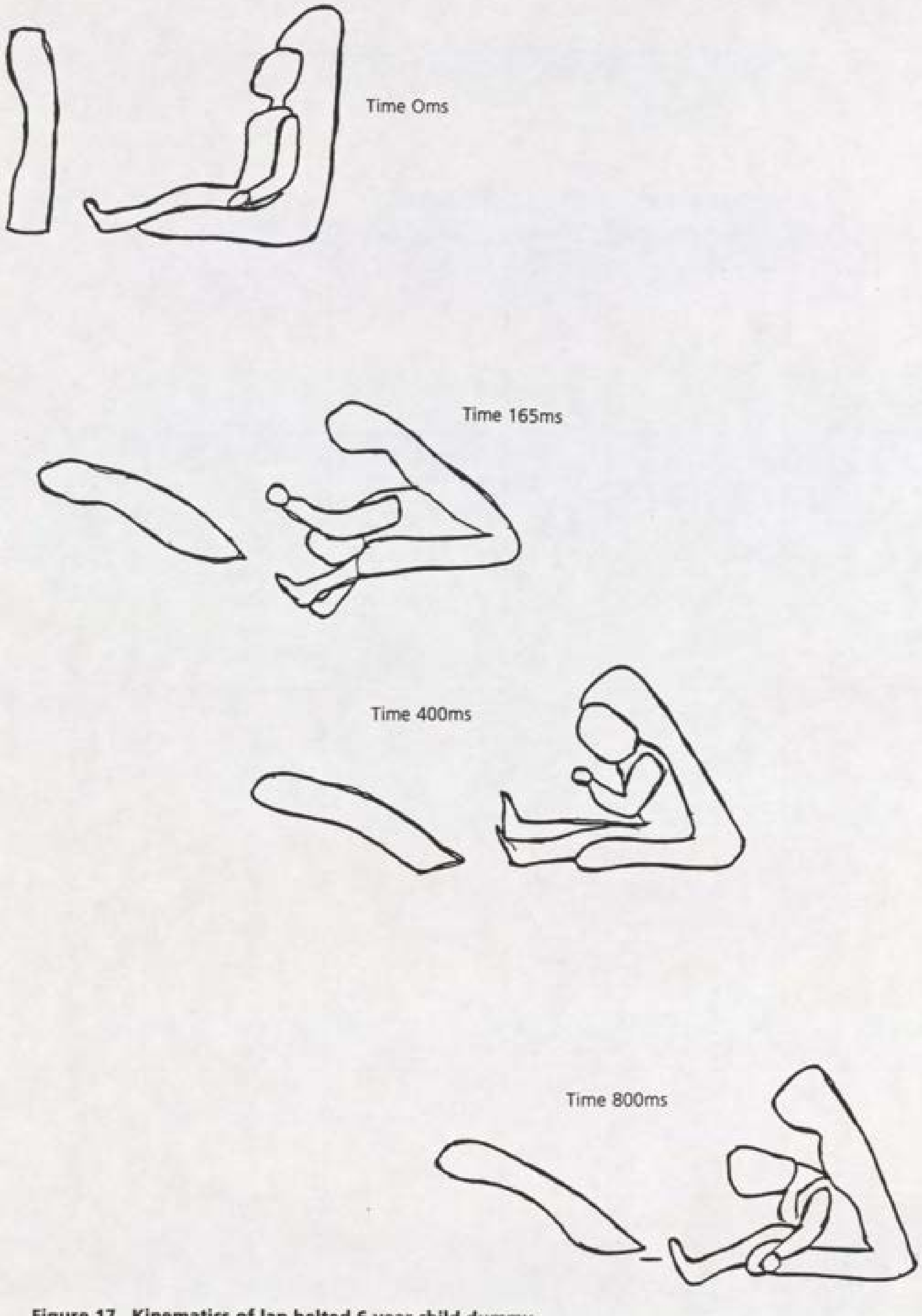


**Figure 17 Kinematics of lap belted 6 year child dummy**

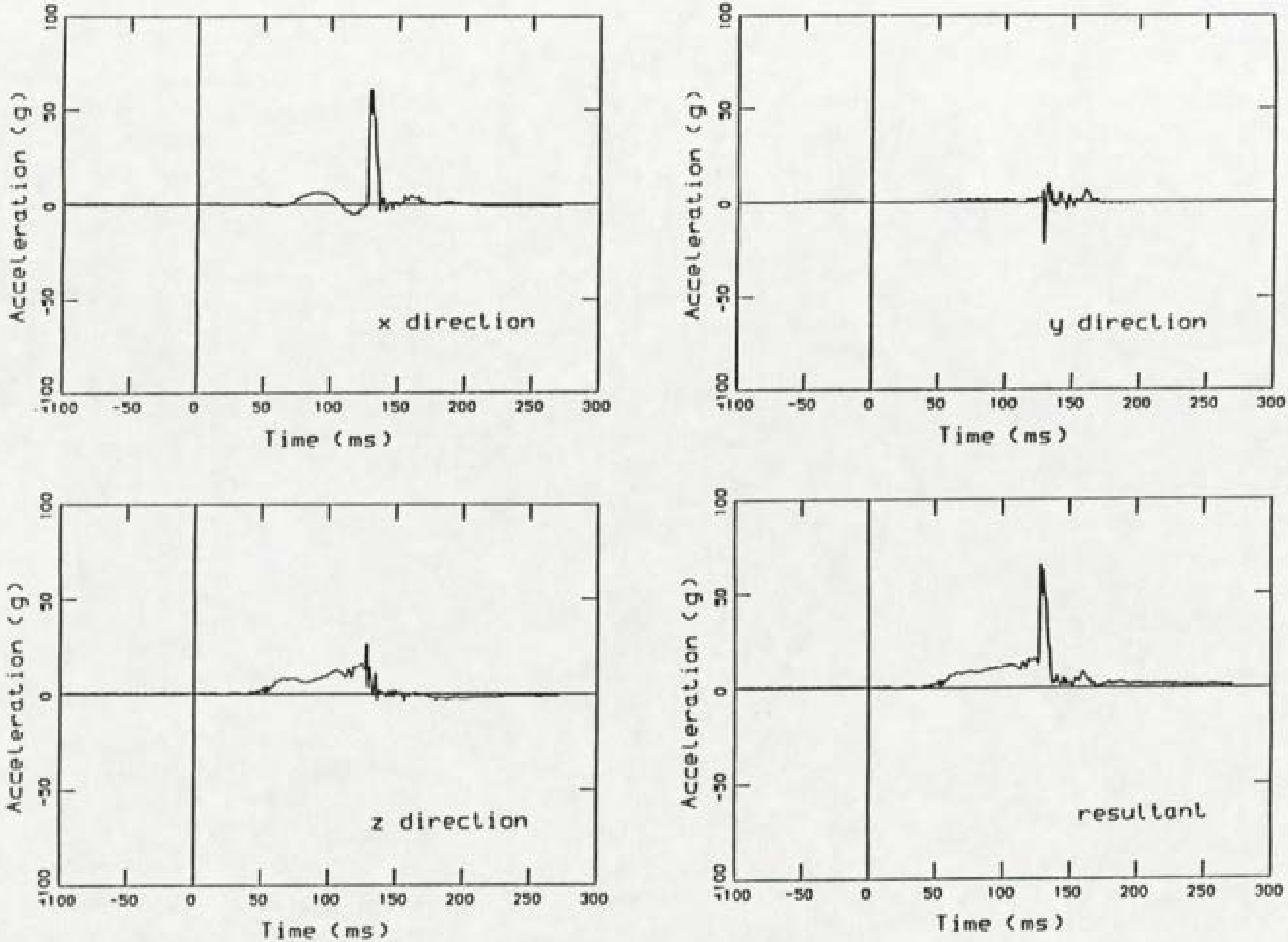


**Figure 18 Head accelerations for lap belted 6 year child dummy**

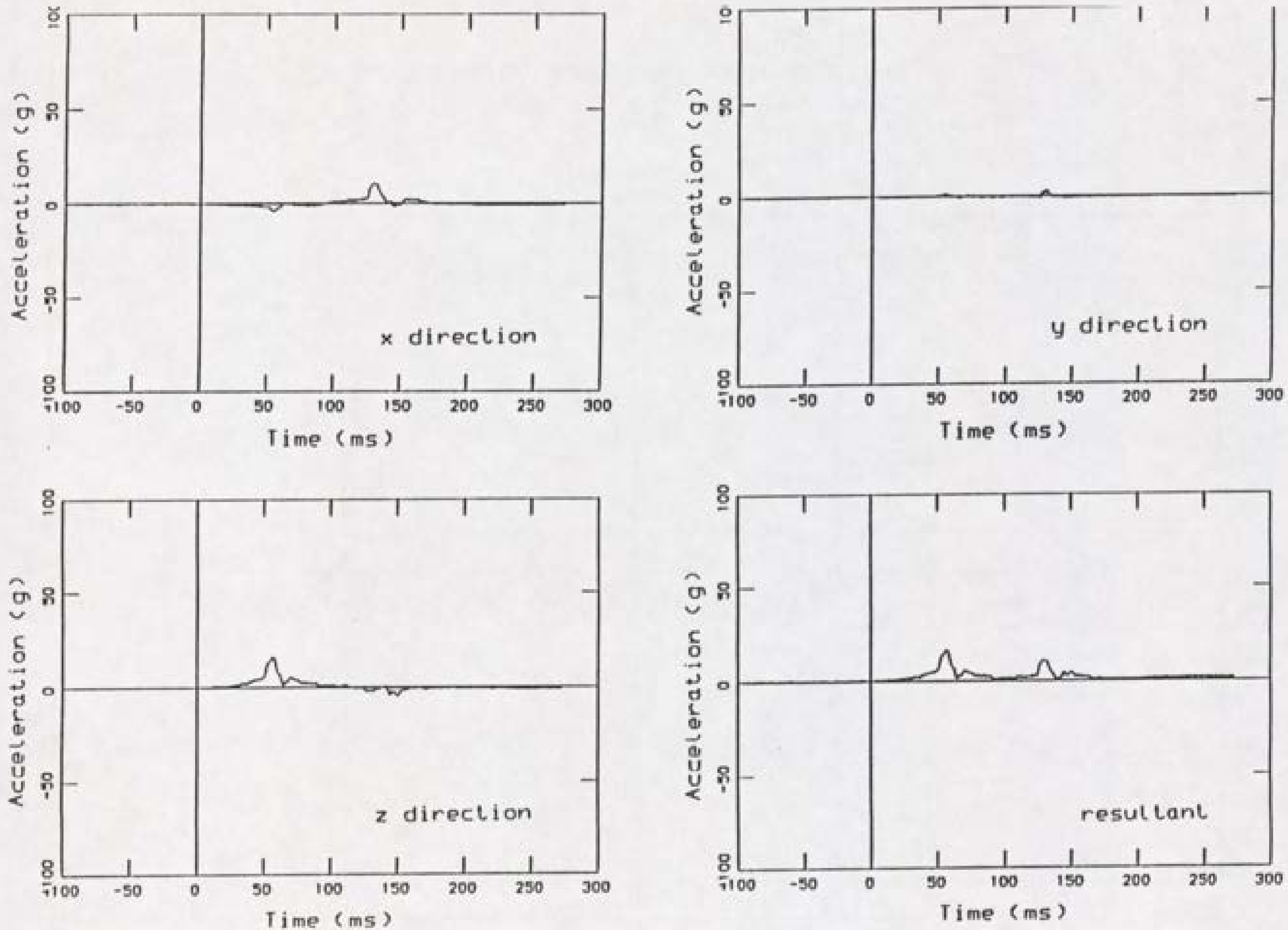


Figure 19 Head accelerations for lap belted and braced 6 year child dummy

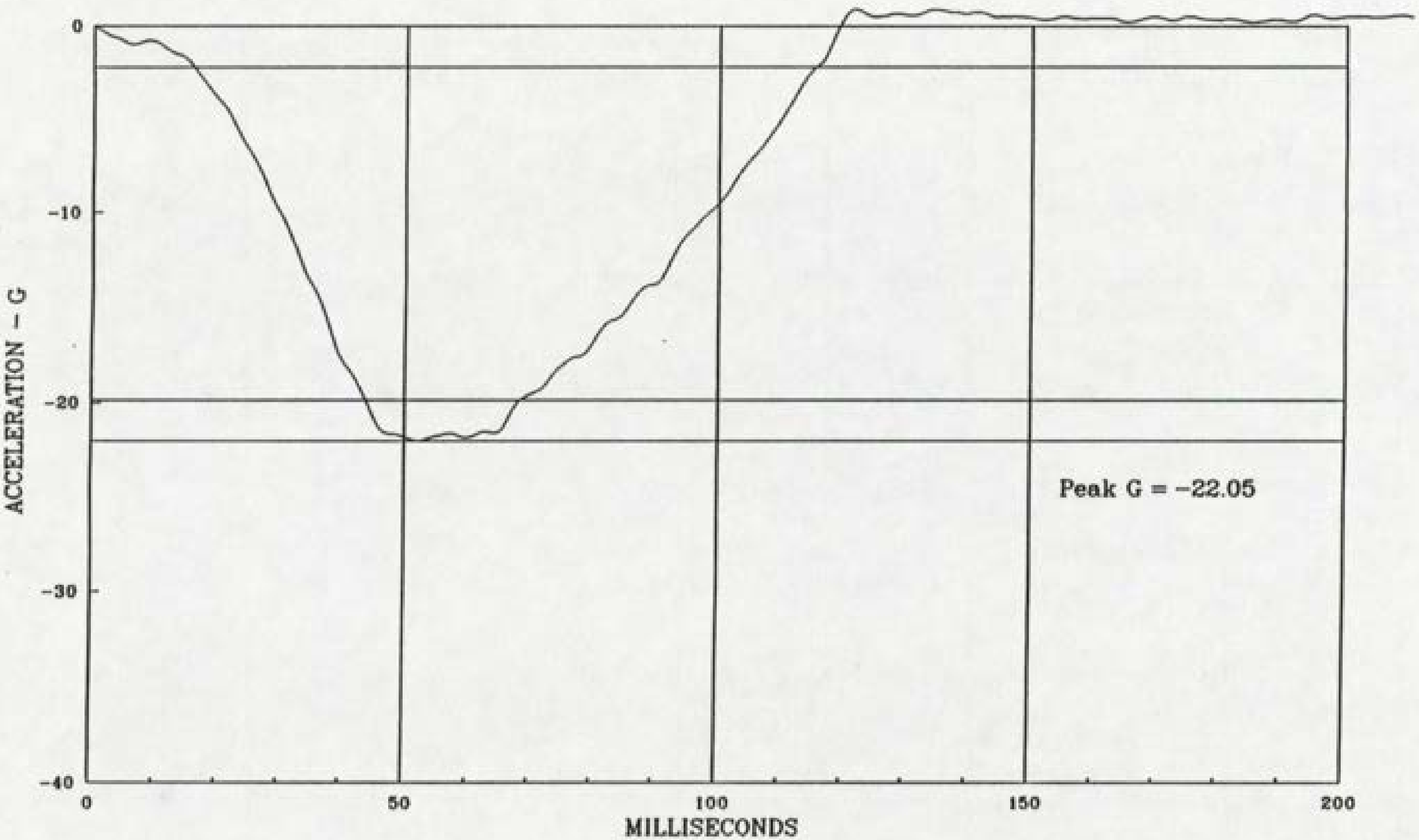


Figure 20 Typical sled acceleration pulse from tests with forward facing restraints

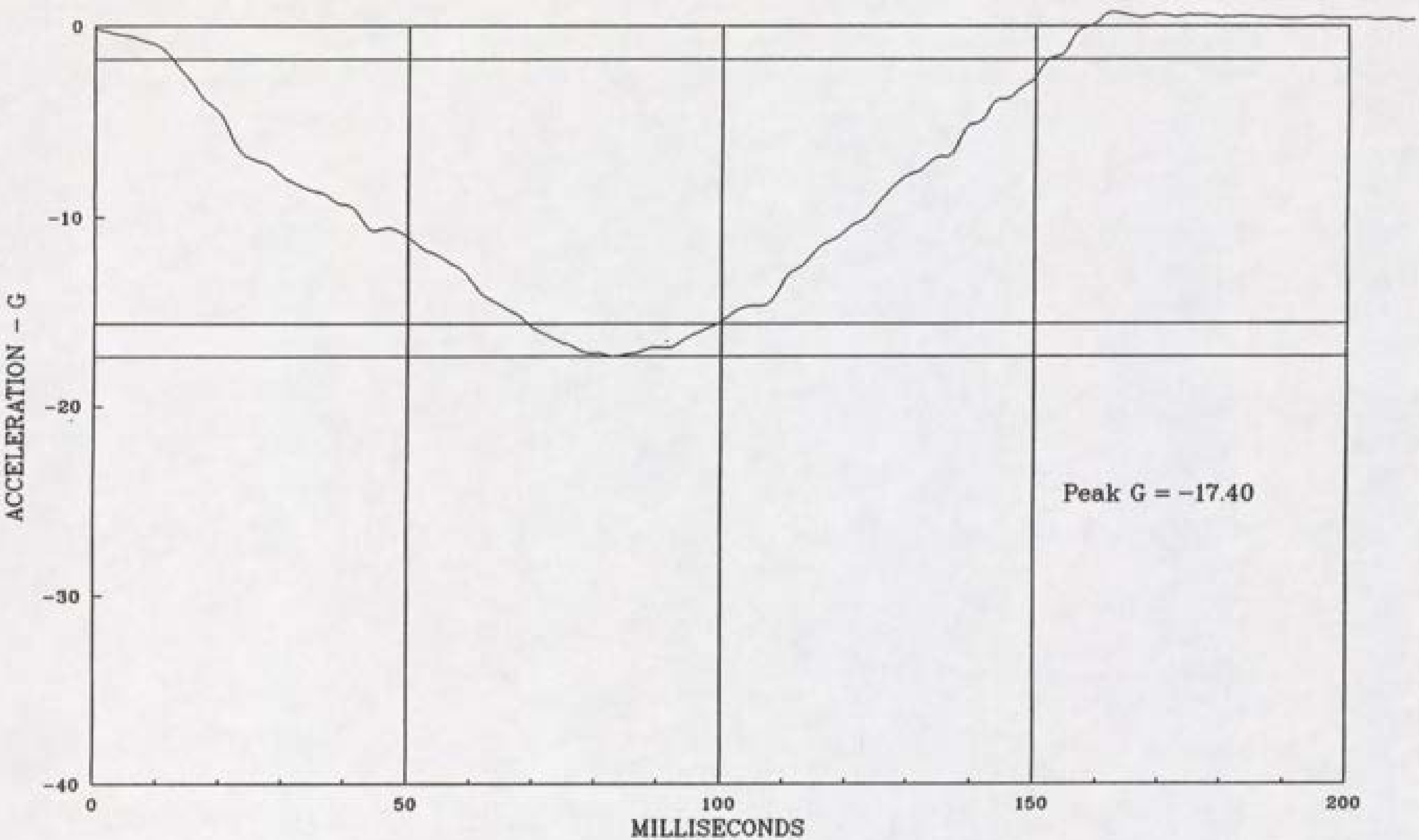


Figure 21 Typical sled acceleration pulse from tests with rearward facing restraints

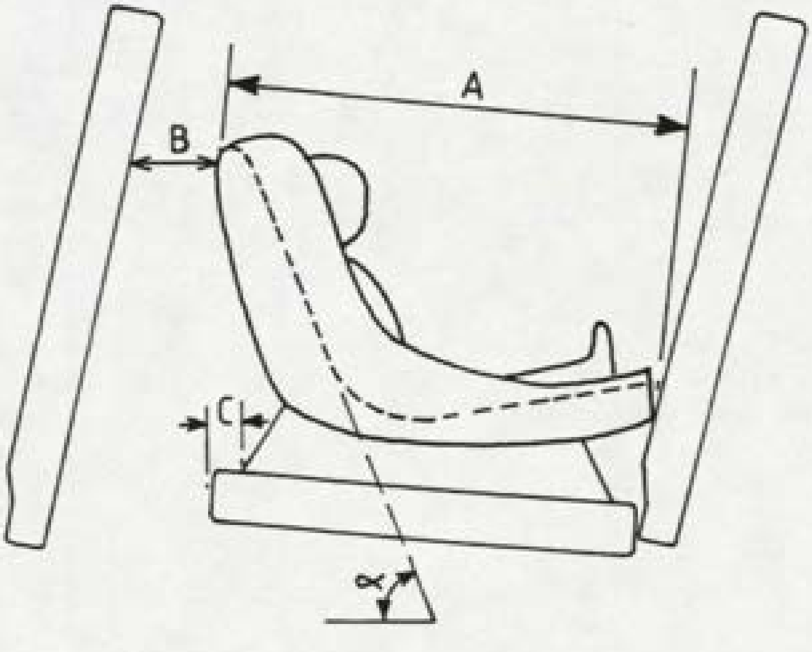


**Figure 22 Position dimensions from rearward facing restraints (ref Table 4)**

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## APPENDIX B AIR NAVIGATION ORDER 1989

### 1 ARTICLE 37

**Public transport of passengers – additional duties of a commander**

37 (1) This article applies to flights for the purpose of the public transport of passengers by aircraft registered in the United Kingdom.

(2) In relation to every flight to which this article applies the commander of the aircraft shall:

(a) ............

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(d) from the moment when, after the embarkation of its passengers for the purpose of taking off, it first moves until after it has taken off, and before it lands until it comes to rest for the purpose of the disembarking of its passengers, and whenever by reason of turbulent air or any emergency occurring during the flight he considers the precaution necessary:

(i) take all reasonable steps to ensure that all passengers of 2 years of age or more are properly secured in their seats by safety belts (with diagonal shoulder strap, where required to be carried) or safety harnesses and that *all passengers under the age of 2 years are properly secured by means of a child restraint device*; and

(ii) ............

### 2 'APPROVED AIRCRAFT EQUIPMENT'

Paragraphs 1 – 3 of Schedule 4 of the Air Navigation Order 1989 explain the layout of the Schedule and list the requirements for the carriage of equipment necessary for airworthiness purposes in the particular circumstances of the flight. Paragraph 3 lists those items which do not have to be of a type approved by the Authority. Child restraint devices, required by Article 37(2)(i), are not on that list and thus must be approved by the Authority.

### 3 EXEMPTIONS

The Authority, by virtue of Article 104 of the Air Navigation Order, may exempt operators or persons from the provisions of the Order, at its discretion. The Authority has issued a general exemption to all operators from parts of Article 37 in order to permit the use of car-type seats, which for technical reasons cannot undergo the approval process required by Schedule 4.