

WHAT MAKES A GOOD RESTRAINT SYSTEM?

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Abstract

Research is being undertaken by Martin Baker Aircraft Company Ltd (MBA) and QinetiQ Ltd, on behalf of the Ministry of Defence, to develop concepts for practical, integrated ejection seat restraint systems. A 2-stage programme of work has been defined to achieve this goal; comparison of the current in service harnesses, leading to the development of future restraint designs.

This paper presents a sample of the results from the first phase of this research programme. It highlights areas where problems occurred and how they were overcome, the harness assessments that have been undertaken and it details the harness tensioning procedure that had to be developed to enable consistent strapping-in of the test manikins.

The aim of the first phase of the programme is to identify and understand the biodynamic interactions of current in-service restraint systems in order to identify any issues that need addressing in future restraint system design.

The QinetiQ decelerator track was used to produce 2 idealised ejection phases and a crash scenario. Four restraint types were assessed, the PCU-56/P (family), PCU15/P (family), which are torso harnesses and the Generation 1 and 4 integrated or combined harnesses. The restraint systems were mounted on a strengthened ejection seat structure, which enabled over 77 runs to be carried out at various seat attitudes including +11Gz, -17.5Gxy and -26.5Gxyz. Hybrid III manikin sensor outputs and tracked motion points were collated for each of these runs in order to determine the effect of the harness restraint.

Introduction

Research is being undertaken by Martin Baker Aircraft Company Ltd (MBA) and QinetiQ Ltd, on behalf of the Ministry of Defence, to develop concepts for practical, integrated ejection seat restraint systems to understand the biomechanical interactions

and to advise the development of future restraint systems. However, in order to develop novel restraint concept systems for ejection seats it is necessary to first understand what makes a good restraint system.

There are three main objectives for an ejection seat restraint harness. It must be capable of keeping the aircrew firmly restrained throughout the flight envelope, including aerobatics, negative G, gusts and emergency escape, whilst remaining comfortable. It must serve as a parachuting harness and must provide good crash restraint on forced landings, undercarriage failure or ditching in the sea. The restraint system must also provide for quick and easy ingress and egress from the cockpit and allow sufficient mobility to permit access to flying controls and be compatible with all flight equipment.

In addition, it is essential that a restraint system does not interfere with normal in-flight duties. Aircrew require mobility, fatigue reduction, and decreased nuisance associated with their restraint system. This, however, is a contradiction of documented needs for takeoff and landing restraint, crash/impact forces restraint, ejection restraint, and parachuting harnesses. It is also inconsistent with the documented need for in flight restraint against G forces associated with turbulence, air combat manoeuvres and departure from controlled flight [1]. Clearly, whatever restraint is provided, the maximum practical protection should be given to minimise the risk of injury to aircrew, whilst not hindering or reducing their performance.

However, this paper will concentrate on the effect of restraint on the aircrew during ejection.

Background

The restraint system is operational throughout flight, ensuring the aircrew remains in a position that enables controlled flight to progress. However, restraint becomes even more essential during ejection. Although over in a matter of seconds, the ejection sequence can be split into 4 main events: the ejection gun phase, rocket motor stage, parachute deployment (including drogue snatch), and seat-man separation.

Ejection Gun Stage

On initiation of the ejection, the occupant is pulled back against the seat at the shoulder by the Harness Power Retraction Unit (HPRU). The seat is then fired clear of the aircraft tail-fin by the ejection gun, which consists of a telescopic arrangement of tubes operated by explosive charges. During the gun phase on most current aircrafts, leg restraints (and on some aircraft, arm restraints) secure the limbs in place to prevent flail injuries. During this stage of the ejection, the occupant can be subjected to a vertical acceleration of up to 22G with modern aircrafts being between 11-15G. The rate of rise for modern aircrafts is of the order of 200G/s and gun separation occurs at approximately 0.225s after initiation, depending on aircraft and ejection seat.

Rocket Motor Stage

Where a rotor motor is fitted, the seat and occupant continue to be propelled clear of the aircraft by an under seat rocket motor which is initiated at gun separation. The combination of ejection gun and rocket motor reduces the peak acceleration

experienced by the occupant by providing a lower average acceleration spread over a longer time period. The rocket motor maintains the level of acceleration of the seat and occupant for a further 0.25s.

Parachute Deployment

The parachute system comprises of a drogue and a main canopy. They allow the seat and occupant to be slowed and, if required, to descend on the drogue parachute to an altitude to allow main parachute deployment

Seat Separation

Once a speed and altitude suitable for a main parachute deployment is obtained, the occupant separates from the seat and descends to the ground under the main parachute.

Test programme

The stages of the ejection sequence were reviewed to determine what the most appropriate test conditions to use in the test programme, in addition to the crash case.

With respect to current in-service harnesses, variants of both the seat-mounted harness (Generation 1 and Generation4, integrated harness) and crew-mounted harness (PCU-56/P and PCU-15/P, torso harness) were tested. These configurations cover the four most widely used restraint systems on ejection seats and encompass both legacy and current designs, as used by both the UK and US operators [2]. It is believed that no current in-service harness gives optimum restraint.

Aim

The overall aim of the research programme is three-fold:

- To compare and understand the performance of current in-service restraint systems
- To combine the desirable features of each harness and design a restraint system
- To develop practical ejection seat restraint systems concepts.

This paper details the trials undertaken to collate quantitative and qualitative data in order to compare the current in-service restraint systems. These data will enable identification and understanding the biodynamic interactions with current in-service restraint systems in order to integrate beneficial features in future restraint design.

The aim of the paper is to detail the methodological approach used in the trials that will provide data to better understand what makes a good restraint system. Therefore, only limited initial analysis is reported and no conclusions about the restraint systems tested have been drawn.

Test equipment

Decelerator track

All the tests were performed using the decelerator track facility at QinetiQ, Farnborough. The track is situated inside a purpose built, environmentally controlled building. It is 50m in length and is capable of accelerating a sled up to 70km/h using

the energy stored in the elastic bungee cords. Retardation levels of up to 50G can also be attained.

Ejection seat

A strengthened generic Mk 16 ejection seat was used for all tests. The seat was strengthened to ensure that it was sufficiently robust to undertake the test programme which involved repeated exposure to acceleration/deceleration pulses that the standard seat was not designed to withstand. The seat was attached to the track sled via a rigid frame. It was positioned such that the manikin's centre of gravity was as low as possible to the track to insure stability, whilst allowing enough space between the manikins feet and test track to allow the manikin's legs to be retracted and restrained in position.

Fitted to the ejection seat was a standard seat harness power retraction unit (HPRU) that allows the harness to be tensioned prior to testing. The HPRU was compressed gas fired rather than explosively fired, to allow the unit to be easily re-used. The HPRU was charged using nitrogen to a pressure of 2000 PSI chosen to 'nominally' represent an Mk 16 HPRU firing, which was maintained for the duration of each test to ensure repeatable tension holding the manikin into the seat.

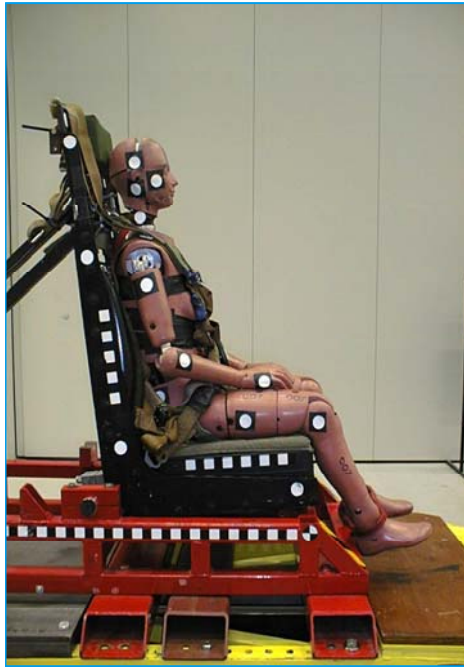
Ejection and crash pulses

Four different test conditions were selected and individual test pulses were derived, which were based on data from previous tests performed by MBA and the capability of the decelerator track. These were:

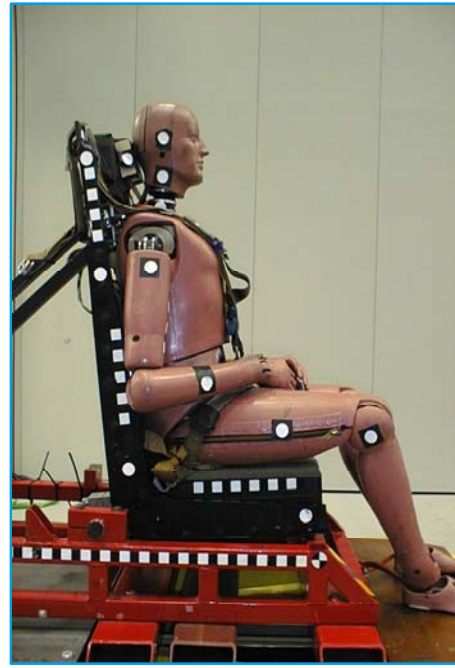
- 17.5 -Gx - drogue deployment
- 17.5 -Gxy - 45° yaw, off axis drogue deployment
- 11.0 +Gz - ejection gun
- 26.5 -Gxyz - 10° yaw, 22° recline, forward crash

Manikins

JPATS case 1 (small) and 6 (large) and Hybrid III 5th%ile female, 50th%ile and 95%ile male manikins were used during the tests (Figure 1). The JPATS manikins were fitted with additional modifications at the shoulder region to improve the likeness and size of the shoulder, and at the hips, with a "skirt and nappy" positioned around the hips and pelvis of the manikin to prevent the harness and clothing riding up into the manikin's joints. The Hybrid III manikins were the standard automotive sitting manikins.



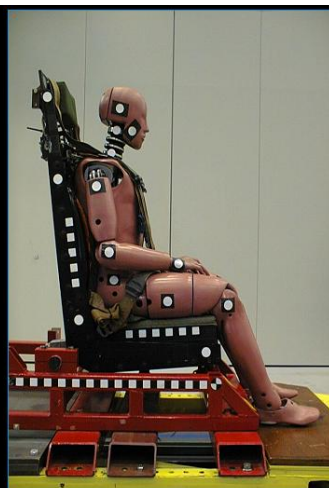
JPATS Case 1



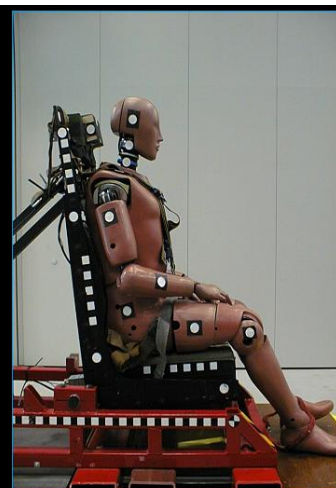
JPATS Case 6



5th%ile



50th%ile



95th%ile

HYBRID III m

Figure 1: Manikins used in tests

Restraint systems

Four current harness designs were investigated (Figure 2):

- US Navy torso harness (PCU-56/P)
- US Air Force torso harness (PCU-15/P & 16/P)
- MBA Generation 1 integrated harness (SCH Gen 1)
- MBA Generation 4 integrated harness (SCH Gen 4)



Figure 2: Four harnesses used for tests

The two torso harnesses are man mounted, whereas the integrated harnesses are fitted to the ejection seat installed in the aircraft. The PCU-15/P & 16/P is donned by putting on a waistcoat and then passing two straps between the legs to attach to the front of the jacket. The PCU-56/P is donned by stepping through the leg holes and pulling up a zip and buckle fastened waistcoat, this is more complex than the PCU-15/P & 16/P. With respect to the integrated harnesses, although they look similar, there are fundamental differences. These differences are in the strapping in procedure and the routing of the harness straps. In addition, the integrated Gen 4 harness was designed to accommodate a greater anthropometric range compared to the integrated Gen 1.

To ensure consistency of restraint fit between harnesses and manikins a procedure was followed. This procedure was drawn up and agreed by both the UK (MBA and QinetiQ) and US government representatives [2]. The procedure detailed webbing lengths and harness webbing tensions for both a tight (30lbf or 13.6kgf) and slack (15lbf or 6.8kgf) harness conditions. Where slack represents a loose harness and tight, (legacy test fit), where it is believed that an aircrew fit lies between the two values.

Clothing

The manikin was dressed in the following clothing:

- Vest, long-johns, shirt, socks, gloves, boots
- Mk 14B flying coverall
- Mk 4 anti-G trousers
- Mk 10B helmet with P/Q mask

In order to maintain consistency between manikins and harnesses, the life preservers, normally worn by aircrew, were not utilised during these tests, as the floatation collars varied for each of the restraint systems.

Test set -up

The test set-up consisted of five main elements; instrumentation, photography, high-speed video, seat orientation and manikin position.

Instrumentation

The data channels included a single axis accelerometer on the sled, a tri-axial accelerometer on the seat for measuring its deceleration and two strain gauged roller shackles located on the harness to measure the loads being transferred through to the shoulders of the manikin.

Inside the manikin were tri-axial accelerometers in the head and chest, a uni-axial load cell between the pelvis and lumbar measuring compression loads, a transducer for measuring chest compression and 6-axis transducers in the upper and lower neck.

Photography

Digital still photographs were taken of the entire manikin set up, from the front and sides pre and post-test. Additional photographs were taken of the shoulders after the HPRU had been activated, to document the position of the shoulders against the seat.

High speed video

Three high-speed video cameras were positioned to capture the manikin movement via the tracking of the markers positioned on the manikin. These markers were positioned on the head pad, seat back, head/helmet centre of gravity (CoG), shoulder joint, and on the arm and leg at various locations to enable motion analysis to occur.

Seat orientation

The seat was orientated in four different positions to reflect the test pulse requirements.

Manikin position

Once strapped into the seat the manikin's hands and legs were tied and retracted to simulate the fully retracted position for active arm and leg restraint. The manikin's arms and legs were similarly positioned for the crash case to ensure consistency, and to minimise flail variations as well as limiting potentially damaging hyperextension of the legs.

Test configuration

The 50th%ile Hybrid III manikin was tested in all seat and harness configurations and formed the baseline for all comparative analysis. For the Gx drogue phase pulse, with the four harness types, the other manikins (5th and 95th Hybrid III and the Case 1 and Case 6 JPATS) were used to study variation from the baseline.

Results

A total of 77 tests were carried out and a large amount of test data collated. Initial analysis of this has been completed.

Discussion

The data analysis splits into two basic areas, motion analysis and injury threshold criteria. Some of the preliminary findings are presented here.

Motion analysis

Video tracking or motion analysis was only carried out on the drogue (G_x) and gun phase (G_z) data.

In order to analyse the motion it was necessary to transfer the video of the test to MPEG format. The image was then made black and white to provide contrast (Figure 3). The required markers to be tracked were identified digitally and the computational analysis then tracked the markers throughout the test sequence.

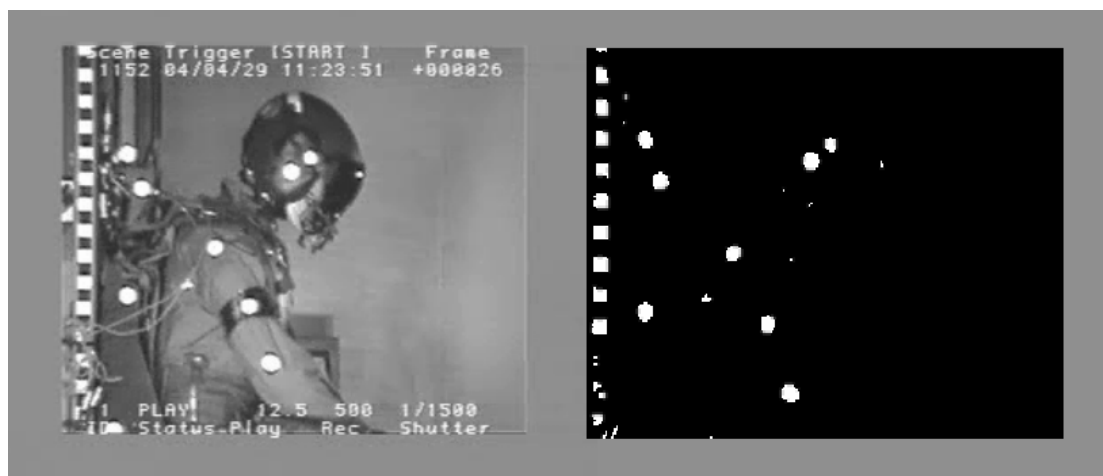


Figure 3: Converting Video into traceable markers

This tracking was relative to known reference markers, to obtain the motion analysis in a format that could be analysed by Microsoft Excel, examples of which are displayed in Figure 4 and Figure 5. Each circular marker was referenced against three consecutive 1-inch squares displayed on the vertical seat structure to the left of the image in Figure 3. The excel output could then be used to compare two marker points on the manikin against each other, i.e. the head movement relative to the shoulder, as all the individual marker data is based on the same seat structure references, thus comparable.

Figure 4 displays the $-G_z$ tracked motion of the shoulder relative to its start point shown on the graph as 0,0. This graph shows the extent of the shoulder roll when the manikin is accelerated laying on it back to represent the $-G_z$ catapult phase. It shows how the shoulder compresses down into the seat pan (seat z-axis) then rolls forward away from the back rest (seat x-axis) and into the restraining harness before recoiling back towards the seat back rest. The two torso harnesses display the least seat x-axis movement.

Figure 5 displays the $-G_x$ tracked movement of the head centre of gravity relative to the shoulder marker, therefore the effect of the shoulder movement is eliminated. This graph shows the extent of the forward 'nod' that occurs when the manikin is accelerated as if on drogue deployment. It shows that the Gen 1 harness allows the most head movement and rotation with the Gen 4 demonstrating the least.

The results obtained from the tracking data can then be compared to the results from the internal instrumentation to determine which movements are undesirable.

Test - Gz(Slack) Occupant - 50th %ile Shoulder Joint Movement Comparison

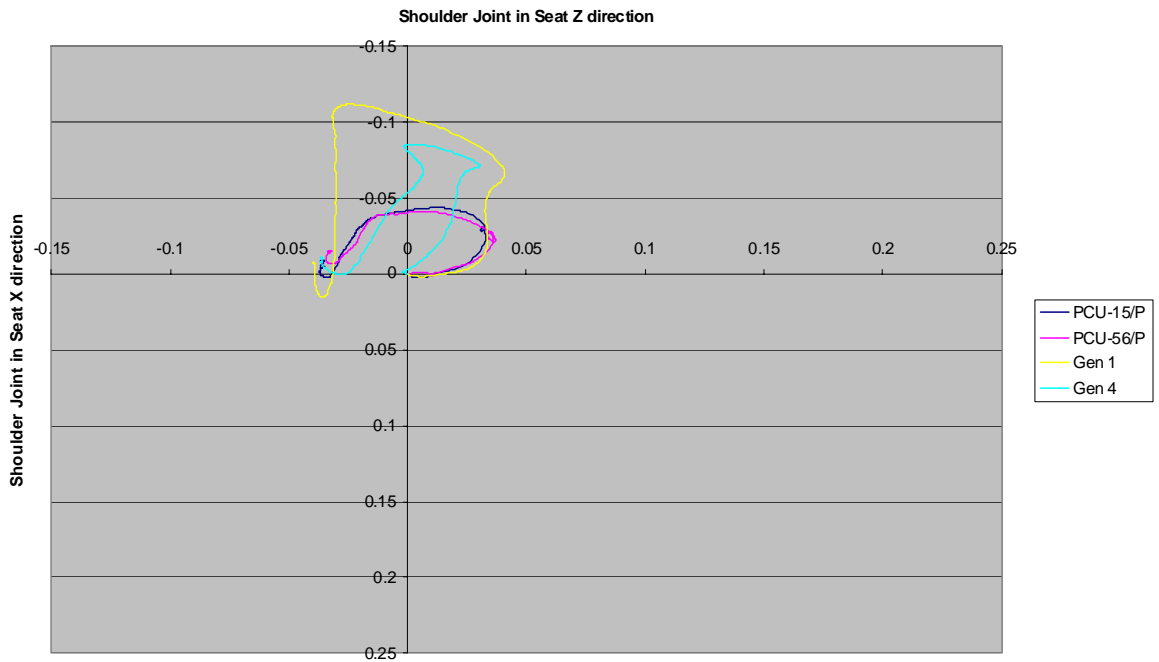


Figure 4: Shoulder motion analysis results for the -Gz pulse comparing all four harnesses fitted in the slack configuration

Test - Gx(Slack) Occupant - 50th %ile Head CoG Movement Comparison

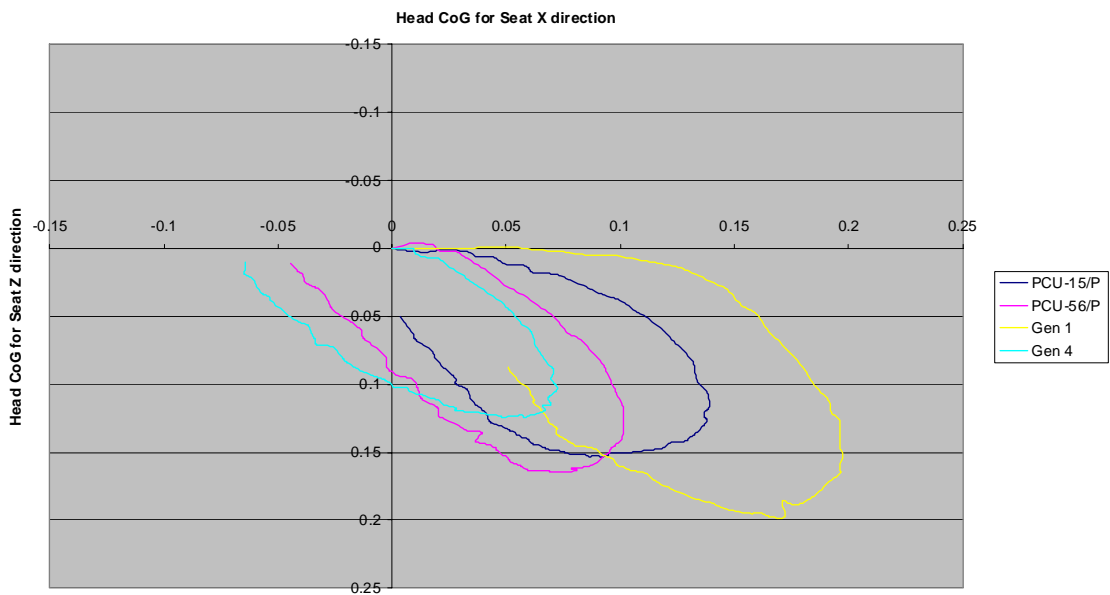


Figure 5: Head motion analysis results for the -Gx pulse comparing all four harnesses fitted in the tight configuration

However, only visible markers could be tracked therefore only these results can be compared against the recorded instrumented manikin data. Markers that passed outside the video window, or were momentarily covered by clothing or cables could not be continually tracked. For example a lack of shoulder tracking data occurred with the 5th, 50th and 95th percentile manikins, for some configurations (Figure 6), this was caused by the clothing dropping into the shoulder joint on the manikin during the deceleration. This was not seen on the JPATS manikins and therefore, may be the result of the additional shoulder supports present on the JPATS manikins, which may have stopped the clothing and markers falling into the joints on the manikin and therefore becoming hidden during the footage.



Figure 6: Demonstrating how the markers can disappear into the manikin's shoulder during the test

Injury threshold criteria

The parameters shown in Table 1 were derived from the instrumentation contained within the seat and manikin. Thirteen of the parameters are standard ejection parameters used to evaluate head, neck and overall injury of the occupant during ejection. The remaining nine parameters are automotive injury requirements used to measure injuries caused by movement within the seat and the loads imposed by the harness.

These data were only included to provide further comparison between the variations in harness design. It should be noted that all of these thresholds are based on the Hybrid III manikin Injury Assessment Reference Values (IARV's) [3] and therefore, the application of them to the JPATS manikins is for research purposes only, where all assumptions can be taken into consideration.

Standard Ejections Parameters	Automotive Parameters (not normally used for ejection analysis)
Upper Neck Tension	
Upper Neck Compression	Positive Chest Deflection*
Upper Neck Shear	Negative Chest Deflection*

Upper Neck NMIX	Delta Chest Deflection*
Upper Neck NMIZ	Thorax Acceleration
Upper Nij	Gx Pelvic Acceleration*
Lower Neck Tension	Gy Pelvis Acceleration*
Lower Neck Compression	Gz Pelvis Acceleration*
Lower Neck Shear	Gx Lumbar Load
Lower Neck NMIX	Gz Lumbar Load
Lower Neck NMIZ	
Lower Nij	
Max MDRC	

Table 1: 29 parameters used to evaluate the harness designs

*Test parameters not recorded by both the case 1 and case 6 manikins as the instrumentation could not be fitted internally.

Two derived data sets; Neck Injury Criteria (Nij) and Neck Moment Index (NMIX) were used to assess combined moment/force and moments at the C0-C1 and C7-T1 positions.

Many of the tests produced results akin to those displayed in **Figure 7**, the ejection gun case (11.0 +Gz), where all the harnesses behaved very similarly and were below the normalised limit. The normalised limit was created to enable each parameter to be displayed on the same axis. This result suggests that for the test configuration and Mk 16 representative pulse used, a high degree of confidence can be given to show that each harness behaves similarly and safely. The results contained within **Figure 7** represent the peak load that was experienced during the ejection for each parameter.

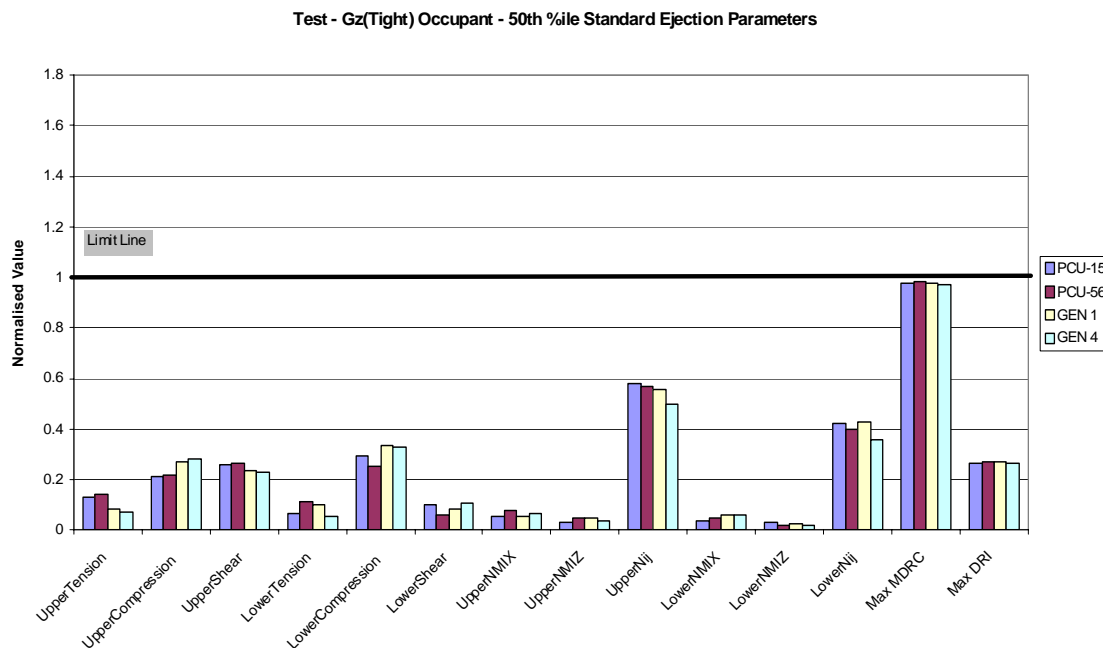


Figure 7: Standard Ejection parameter results for the -Gz pulse comparing all four harnesses fitted in the tight configuration

Alternatively, results like those displayed in Figure 8, for the off axis drogue deployment case (17.5-Gxy, 45° yaw), display a marked increase in values across all of the standard ejection parameters, several of which exceed the normalised limit. It is thought that these variations are due to differences in the degree of lateral restraint afforded by the different harnesses.

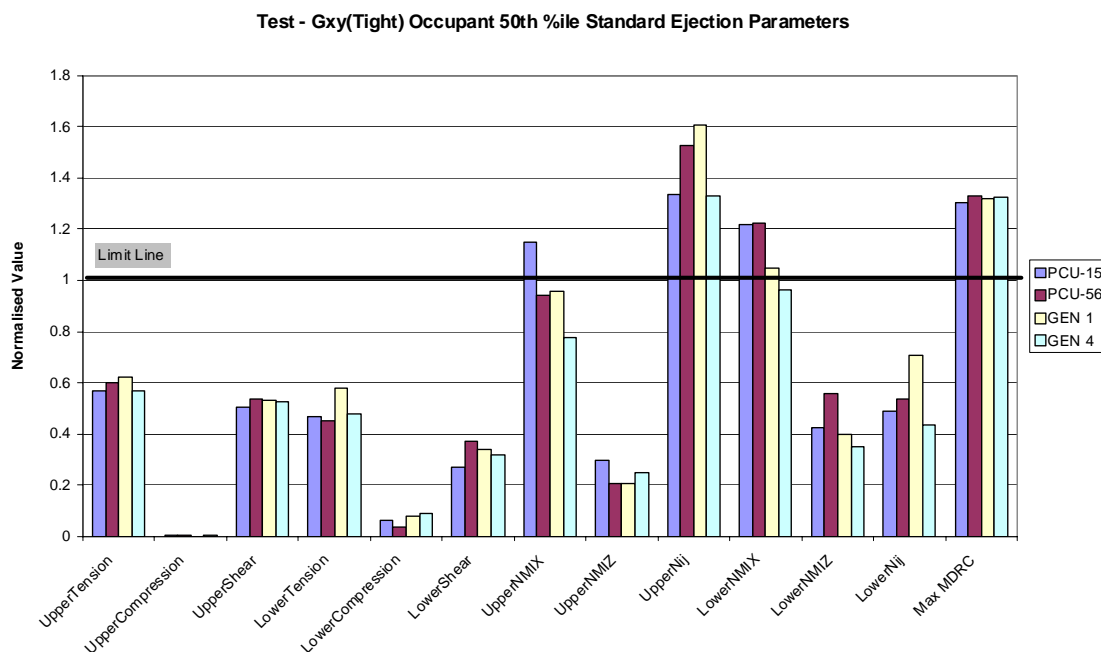


Figure 8: Standard Ejection parameter results for the -Gxy pulse comparing all four harnesses fitted in the tight configuration

At this stage in the analysis of the data it is not possible to identify what makes a good restraint system. Further analysis is being carried out to determine the best harness features to enable initial input to designs for a new novel restraint system.

Summary

The trials programme has been successfully completed, comparing the response of four different harness systems, across the full anthropometric range, with two different degrees of restraint (tight and slack).

A large amount data have been collated and the analysis is still in progress. Once the injury threshold data have been analysed it will be necessary to relate the findings to accident injury data, before a novel restraint concept can be developed.

Disclaimer

These tests reported in this paper form part of an applied research project to understand ejection restraint, which is still ongoing. The results reported here are in no way meant to be used to determine which of the harnesses tested are superior.

References

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2. Bradstock-Knight D., Ransley M., “Test procedure – QinetiQ/MBA Novel restraints research and development project” MBA/QTP/651, April 2004.
3. “Hybrid III: The first human-like crash test dummy” Edited by S.H. Backaitais & H.J. Mertz. SEA PT-44, 1994.