ESTABLISHING A SPINAL INJURY CRITERION FOR MILITARY SEATS

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ABSTRACT

Currently, military specifications require use of an acceleration-time criterion to assess the physiological acceptability of crash resistant seats and restraint systems. With the evolution of crash test dummies which now exhibit greater bio-fidelic performance, military researchers are considering "direct force" measurements taken within the Hybrid III anthropomorphic test device (ATD) as an alternate evaluation criterion. The Federal Aviation Administration (FAA) recently established such a criterion as part of a new dynamic test requirement for the certification of airline passenger seats.[1] Prior to military tri-service implementation of a similar requirement, validation of the methodolgy with the "aerospace" model of the Hybrid III manikin was necessary. This paper describes the test program conducted with Hybrid III crash test dummies to establish a lumbar spinal load injury criterion for military crash resistant seat compliance testing. The effort was sponsored under the Naval Air Systems Command's (PMA-202) Advanced Crashworthy Aircrew Survival Systems (ACASS) Program.

Dynamic testing was conducted on the Horizontal Accelerator Facility at the Naval Air Warfare Center, Aircraft Division, Warminster, PA. The test program examined the lumbar spinal response of Hybrid III test dummies when exposed to predominantly vertical helicopter crash pulses under controlled laboratory conditions. Sufficient data was acquired to conduct a statistical analysis of the Hybrid III's lumbar spine response to compressive loading (i.e., + Gz headward direction). The analysis supports the recommendation to employ lumbar force as a primary physiological criterion for military crash resistant seat compliance. Also, the merits of using this injury indicator during escape system testing are discussed.

INTRODUCTION

Military specifications do not state performance requirements in terms of specific injury mechanisms or quantifiable injury threshold levels. Typically, performance requirements for crash resistant seats and restraints are "indirectly" validated against potential injury during qualification testing. For example, MIL-STD-1290[2] stipulates an impact velocity change parameter for the aircraft's crash survivability requirement which is based on mishap data from operational aircraft accidents and crash testing of specific aircraft models. Crash resistant systems proposed by industry must meet structural strength requirements, and an occupant survivability criterion based upon the Eiband Curve[3] when tested to the standard's generic crash pulse. The Eiband Curve criterion essentially defines a maximum acceleration-time profile for the headward (+ Gz) direction to which the seat/occupant response must comply (Figure 1). However, since injury mechanisms are intrinsically related to the applied force sustained by the body member, military crash safety researchers are now investigating the feasibility of employing a "direct" parameter. In the case of vertebral fractures, a "spinal force" parameter is proposed. Although this investigation focused on lumbar forces to establish an alternative criterion to the Eiband Curve, the process can be applied to other injury mechanisms during the development/qualification phase of crash resistant systems. As part of the ACASS program, test methodolgy changes are under consideration for various injury mechanisms for the head, brain, cervical neck, face, upper torso/thorax, lower limbs, and lumbar spine. Reference 4 reviews injury criteria which provide the basis for advanced manikin use in the development of automotive restraint technology.

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**
4. TITLE AND SUBTITLE **Establishing a Spinal Injury Criterion for Military Seats**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Air Warfare Center,Aircraft Division,Patuxent River,MD,20670**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

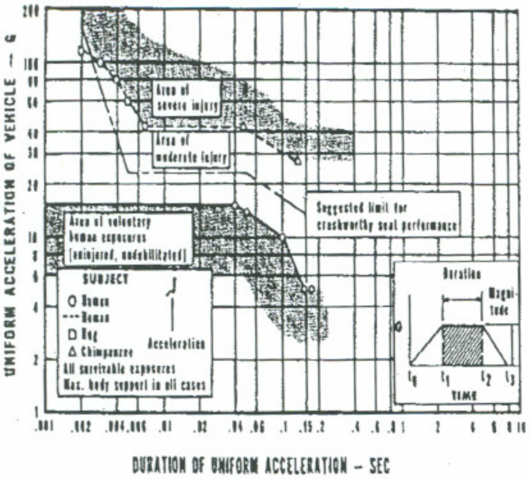

Figure 1: EIBAND Spinal Injury Tolerance Curve

Background

Minimal crash impact testing with volunteer subjects has been conducted since Colonel Stapp[5] ran his rocket sled tests in the 1950s and the Naval Air Medical Research Laboratory (NAMRL)[6] conducted head/neck acceleration tests with military volunteers in the 1970s. Since then, military and automotive researchers have concentrated their efforts on compiling biomedical data from cadaver tests and documented human accidents to derive injury assessment criteria. The Society of Automotive Engineers (SAE) has formally published several documents[7,8,9] which summarize much of the biomedical injury data currently available. A prime example of an application of this data is the National Highway Transportation Safety Administration's (NHTSA) Head Injury Criterion (HIC), currently used as a "pass/fail" marker for automotive restraint systems during barrier impact compliance testing of new cars under Federal Motor Vehicle Safety Standard 208.

Reference 10 describes an initial attempt to modify Part 572 and VIP-95 test dummies with lumbar load cells to establish a methodology for measuring spinal force in crash tests. Data from the rigid seat tests did not exhibit any differences in accelerations or forces measured before or after installation of the spinal load cells. However, a trend was observed in the data from the energy absorbing (EA) seat tests. Modification of the manikins resulted in chest x-components significantly higher during the tests with EA seats, indicating a possible alteration of torso flexural characteristics. Also, x-components of the head indicated that some alteration of neck response characteristics may have been produced during the modification process. The authors, however, concluded that forces and moments in the spine of an ATD could be measured without adversely affecting the flexural characteristics of the lumbar spine.

The FAA's newly adopted seat dynamic performance standard which incorporates a lumbar spinal load injury criterion is described in Reference 11. A maximum compressive load of 1,500 pounds between the pelvis and the lumbar spine of the Part 572B, 50th percentile male ATD has been established for the crash environment in which the predominant impact load component is directed along the spinal column of the occupant. Figure 2 depicts the installation of the pelvic lumbar spine load cell in a Part 572B anthropomorphic dummy associated with the FAA's standard.

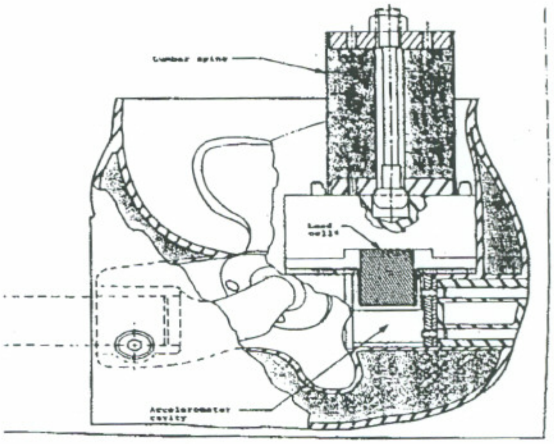

Figure 2: Part 572 Pelvic Segment with Lumbar Spine and Load Cell Assembly

A key element in the application of injury threshold levels to the evaluation of a system's crash impact performance is the availability of a reliable crash test dummy capable of providing reproducible results in controlled testing. The Hybrid III is a crash test dummy developed by General Motors Corporation in the 1970s to improve the biofidelity and injury prediction capability of test surrogates. Parameters related to impact injury, such as head acceleration, neck forces/moments, thorax accelerations, femur forces, and lumbar forces/moments can be measured in currently available Hybrid III ATDs. Reference 12 describes biofidelic enhancements to the Hybrid III design which support its use in predicting human injury during simulated automobile crash tests. Although a direct correlation between the Hybrid III's biomechanical response and the human has not been fully achieved, the Hybrid III can serve as a viable test device to allow a comparative evaluation of the injury mitigation capabilities of proposed military crash resistant systems. Modifications to Hybrid III ATDs for use in the military test environment are described in Reference 13.

Test Objectives

Note that a direct correlation between the Hybrid III's impact performance and human injury tolerance was not considered within the scope of this program. Test program objectives were intended to support the establishment of a new Navy injury criterion based on direct measurements of lumbar spinal forces/moments taken during dynamic crash tests of candidate crash resistant systems. Specifically, the following test objectives were established:

(a) To quantify the effects of various load paths within the Hybrid III's lumbar spine construction.

(b) To determine the effects of the following variables :

- Hybrid III size/weight;
- Upper torso stiffness;
- Crash pulse parameters such as:
  - Peak acceleration;
  - Pulse velocity-change.

The influence of these variables on the response of the Hybrid III's lumbar spine to typical crash impulses was studied by an analysis of variance (ANOVA) statistical method.

EXPERIMENTAL PROCEDURE

Test Facility

The dynamic tests were conducted at the Naval Air Warfare Center Aircraft Division Horizontal Accelerator Facility previously located in Warminster, PA. The Horizontal Accelerator simulates typical decelerative crash forces associated with vehicle mishaps by reversing the orientation of the test article and accelerating the system from an initial velocity of zero. It consists of three main assemblies: (1) accelerating mechanism, (2) test sled, and (3) a set of guide rails, 100 feet long. The accelerating mechanism is a 12-inch HYGE actuator which generates a maximum force of 225,000 pounds of gross thrust.

Test Articles

Test Seat / Restraint System

The test article consisted of a rigid seat structure configured with a standard Mil-S-58095 five-point restraint system. The Mil-S-58095 restraint's inertia reel was replaced with an adjustable fixed anchor fitting to preclude the possibility of inertia reel failures during this study. Since the restraint system would experience minimal crash loads under the predominant vertical impact vector during this test series, replacement of test restraints was made sparingly.

The generic seat system (non-energy absorbing) was mounted to the sled platform in an orientation to simulate the vertical impact mode. The test seat was rotated 90 degrees to the vertical axis to align the manikin's spine parallel to the input crash pulse. Standard operational seat cushions were not used to preclude any adverse amplification factor in the controlled testing.

Figure 3 shows a post-test side view of the 95th percentile ATD seated in the test seat as located within the vertical orientation test fixture.

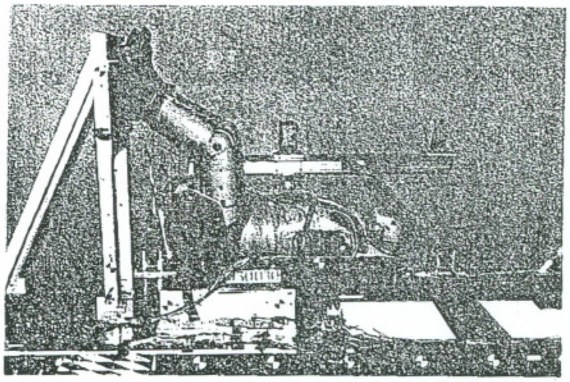

Figure 3: Post-test Side View of 95th Percentile ATD Showing Vertical-Orientation Test Fixture: Run No. 95030

Anthropomorphic Test Devices (ATD)

Hybrid III male ATDs (5th, 50th and 95th percentiles) instrumented with lumbar load cells were seated within the test seat. The Hybrid III lumbar spine is a polyacrylate elastomer member with molded-in end plates for attachment between the thoracic spine and pelvis. A curved lumbar spine is incorporated in the automotive configuration to replicate the typical automotive seated driving position. However, the "erect" (i.e., straight) lumbar spine and the articulated hip assembly of the "aerospace model" were selected for this test series to permit axial loading of the spinal column. In addition to these design modifications, structural enhancements to the shoulder-clavicular assembly have been incorporated into the aerospace configurations.

Prior to the test phase of this program, each of the ATDs were disassembled to identify alternate load paths present within the upper torso. The abdominal insert assemblies presented a secondary load path for reacting a portion of upper torso mass during compressive loading of the spinal column. Each of the ATD's upper torso components were scale-weighed. In addition, the test dummies were electronically weighed "with and without" the abdominal inserts positioned to determine the 1g effect of the alternate load path. Table II lists the component weights, total weights, and delta measurements attributed to the inserts for each of the test dummies.

TEST CONDITIONS

The crash pulse parameters shown below (Table I) define the impact profiles which were employed during the test program. The pulse shape selected was essentially a "half-sine" waveform, with peak acceleration and velocity-change the critical parameters defining the severity of the crash pulse. Pulse severity was based on the premise that the analysis would be conducted on a "fixed" seat structure and, therefore, would not provide any energy absorption/load-limiting effect to the seated occupant.

TABLE I: SUMMARY OF IMPACT PARAMETERS

Vector	Peak Acceleration (G)	Velocity Change (fps)
Gz	10	20
Gz	10	25
Gz	10	30
Gz	20	20
Gz	20	25
Gz	20	30
Gz	30	20
Gz	30	25
Gz	30	30

Figure 4 shows sample overlay plots of the test facility's crash pulse waveforms selected for this test program. Representative pulse signatures for the three peak accelerations at the 25 fps velocity change level are given.

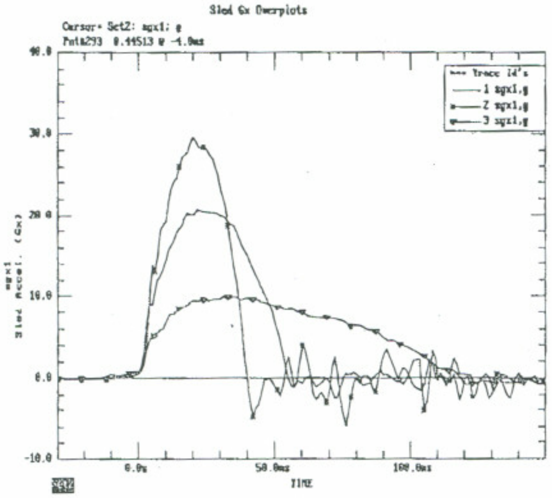

Figure 4: Sled Impulse Showing 25 fps Velocity Change of 10, 20, 30 Gz Peak Accelerations

During Phase I, the "20 G" peak Gx Sled (i.e., + Gz relative to ATD) parameter was maintained at a mean of 20.49 Gs with a standard deviation of 0.24. Velocities were also closely controlled: for example, the "20 fps" parameter had a 95 percent confidence interval between 20.07 to 20.66 fps.

TEST RESULTS

Discussion of Test Variables

The initial test series studied the effects of velocity, ATD size, torso restraint, and the abdominal insert load path on the Hybrid III's lumbar spine response to compressive loading. Test conditions were established to study the influence on lumbar spinal loading by the following independent test variables:

- Velocity change of the crash pulse; (3 ea)
- ATD percentile sizes ; (3 ea)
- ATD head/ torso ; ("restrained" or "free")
- ATD abdominal insert; ("present" or "absent")

- Peak acceleration of the crash pulse; (3 ea) (incorporated during Phase II)

One repetition was conducted for each test condition. Initially, peak acceleration effects were not considered; all trials during the initial series were conducted at the same 20 G peak amplitude. Subsequent to the initial assessment, a supplemental test series (Phase II) was conducted to include the effects of peak acceleration, adding trials at 10 and 30 Gs. This was possible once the effects of torso restraint and the abdominal insert load path were quantified as minimal during the initial series at the 20 G peak acceleration level. Phase II consisted of an additional 36 tests, keeping the upper torso restrained and each of the abdominal inserts present.

Influence of Abdominal Inserts

Figure 5 shows the Hybrid III ATD with the abdominal insert removed for the 95th percentile ATD.

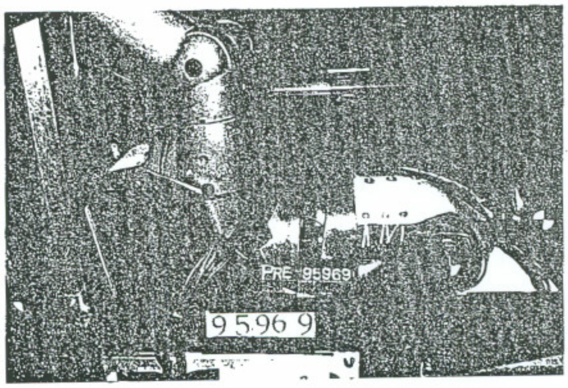

Figure 5: Pre-test Side View of 95th Percentile ATD with Abdominal Insert Removed: Run No. 95969

A preliminary assessment of lumbar load test data measured during earlier Navy test programs had indicated that the Hybrid III's lumbar spinal load cell did not measure the total force theoretically generated by the upper torso mass during crash impact testing. The influence of the abdominal insert was investigated relative to this apparent anomaly.

Table II shows the delta readings between the normal scale measurements and a static 1 g measurement of the upper torso as measured by the lumbar load cell with and without the abdominal inserts positioned. The influence of the abdominal insert is evident from the 1 g rotation weighings resulting in weight deltas ranging from a minimum of 6.8 pounds for the 5th percentile manikin to a maximim of 26.9 pounds for the 95th percentile manikin. The higher mass readings recorded with the abdominal inserts removed support the assertion that the inserts produce an alternate load path to compressive/axial spinal loading.

Also of significance was the finding that the upper torso structure of the 95th percentile ATD did not exhibit a proportional increase of mass as compared to the differential between the 5th versus 50th percentiles. Subsequent load cell measurements of the 95th-percentile ATD with the insert installed reduced the "effective" upper torso mass to 69.3 pounds.

This result coupled with what appears to be nonlinear scaling of the 95th percentile's upper torso mass presented a set of test dummies which skewed the test results. It should be noted that at this time, essentially no configuration control of the aerospace model Hybrid III ATD exists. Caution should be exercised when comparing test data from various facilities, or even within the same test organization, using this particular configuration of the basic Hybrid III design.

TABLE II: Hybrid III Aerospace ATD Weights

ATD Size (%)	Total Weight (lbs) (Scale)	Upper Torso Weight (lbs) (Scale)	Upper Torso Weight with Abd. Insert (lbs) (Load Cell)	Upper Torso Weight without Abd. Insert (lbs) (Load Cell)	Mean Delta Weight (lbs) (Load Cell)	Abd. Insert Weight (lbs)
5th	160	78.6	72.5	79.3	6.8	1.2
50th	179	90.5	84.3	96.0	12.0	1.4
95th	209	97.5	69.3	96.2	26.9	5.6

Upper Torso Mass consisted of following components:

- Head/neck assembly
- Upper torso assembly minus forearms
- Instrumentation (tri-ax accelerometers in head & thorax; load cells in lower neck & lumbar spine)
- Skin & abdominal inserts

Observations

Figure 6 displays the characteristic response of the Hybrid III's lumbar spinal column when subjected to a typical half-sine crash pulse as produced by this test facility. The phase lags associated between the thorax and pelvis accelerations typically recorded during this test series are also evident.

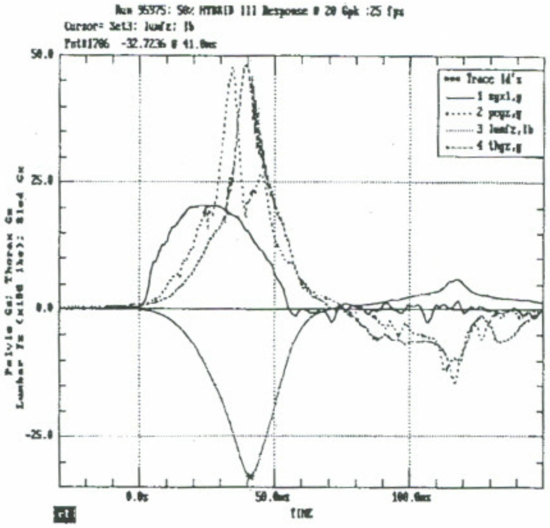

Figure 6: Typical Vertical Response Parameters of 50th Percentile Hybrid III ATD at 20 G Peak; 25 fps Velocity Change

During the Phase II test series, analysis of the 50th percentile ATD response produced a mean dynamic "effective" upper torso mass of 71.8 pounds (standard deviation = 6.4) for the 12 runs with the 50th percentile ATD (torso "restrained" and abdomen "present") as compared to the static scale weight value of 90.5 pounds and 84.3 pounds with the abdominal insert positioned. Evidently, the insert produced a dynamic delta of 18.7 pounds compared to the static delta value of 12.0 pounds. This infers that the abdominal inserts produce an unloading effect on the Hybrid III's spinal column during compressive loading. Consideration should be given to this effect whenever measured lumbar loads within the Hybrid III are compared to ultimate vertebral failure levels.

TABLE III: Test Results; Means (Phases I & II)

Delta Vel. (fps)	Pk. Sled Gx (G's)	5th Pelv. Gz (G's)	5th Thor. Gz (G's)	5th Lum. Fz (lbs)	50th Pelv. Gz (G's)	50th Thor. Gz (G's)	50th Lum. Fz (lbs)	95th Pelv. Gz (G's)	95th Thor. Gz (G's)	95th Lum. Fz (lbs)
20	10	17.3	16.9	1056	19.2	21.7	1511	16.4	20.3	1415
20	20	32.5	33.3	2314	39.8	42.9	2641	28.9	48.6	2487
20	30	38.4	45.3	2530	50.6	52.6	3185	44.4	42.7	3127
25	10	18.5	18.1	1123	18.1	19.6	1514	16.5	20.9	1373
25	20	36.0	40.1	2664	47.1	47.9	3280	33.2	54.0	2700
25	30	56.6	57.1	3405	68.5	72.5	4429	50.9	55.6	4297
30	10	18.1	18.0	1129	18.4	19.9	1550	16.6	20.8	1357
30	20	33.1	38.9	2405	39.2	45.8	3397	34.9	51.4	2787
30	30	64.5	62.1	3845	65.9	72.7	4872	56.4	67.3	4780

Test Conditions:
- Upper Torso Restrained
- Abdominal Insert Positioned
- Table represents 54 Trials (18 [Phase I] + 36 [Phase II]); "Combined Effects" of Delta V, Gpk & ATD Size

GLM 1

A General Linear Model (GLM) analysis addressed the effect of manikin size and velocity change on lumbar load where the head and torso were restrained and the abdomen was in place. Lumbar load was affected by manikin size (F= 104.64, p= .000) and velocity change (F= 48.99, p= .000), where there was an interaction (F= 11, p= .001) between these variables. Figure 7 represents this interaction. The nonlinear effect of manikin size on the lumbar load variable was somewhat unexpected and prompted the mass survey of the test manikins' upper torsos shown in Table II.

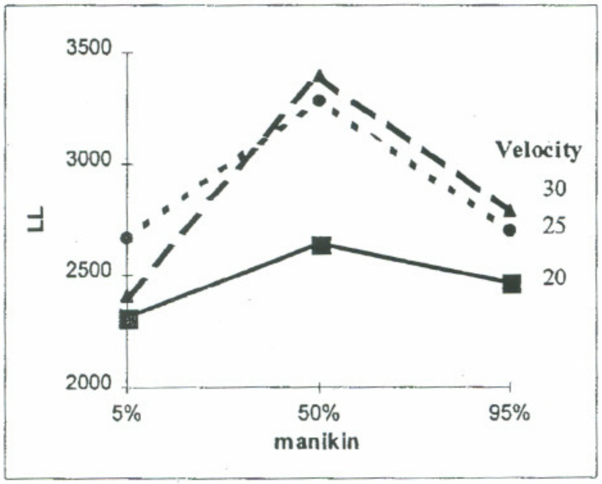

Figure 7. Effect of Manikin Size and Sled Velocity Change

GLM 2

A General Linear Model analysis addressed the effect of manikin size and abdomen placement on lumbar load where the head and torso were restrained and the velocity was maintained at 25 fps. Lumbar load was affected by manikin size (F= 55.29, p= .000) and abdomen placement (F= 7.65, p= .024); but there was no interaction between these variables. The influence of the abdominal insert when present, shows an unloading effect on lumbar force (Fz) levels. Lumbar force measurements (Fz) for the three test manikins selected for this test series again indicates a nonlinear dynamic characteristic. The results appear consistent with the measured weights of the upper torsos of the three test specimens as shown in Table II.

Figures 8 and 9 represent these results.

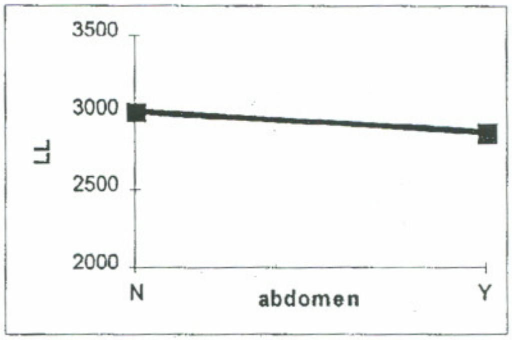

Figure 8: Effect of Abdomen Insert Placement

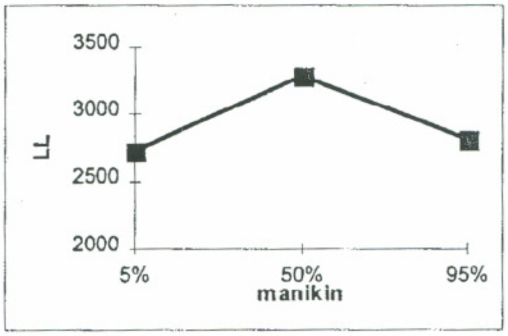

Figure 9: Effect of Manikin Size

Lumbar Force Tolerance Criteria

Figure 10 provides a lumbar force tolerance curve normalized for occupant total weight. This curve was developed for the Automatic Energy Absorber (AEA)

Program[14] currently investigating the possiblity of producing a load-limiter which optimizes performance relative to lumbar load response as opposed to the existing criterion of seat/pelvic acceleration (i.e., Eiband Curve).

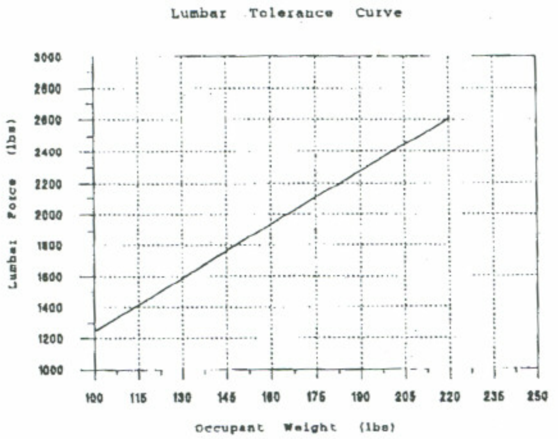

Figure 10: Proposed Lumbar Load Tolerance Curve

The parameters of the sled's impact pulse (Table I) were selected for comparability to known load-limiting (energy absorbing) seat design responses.[15] This approach was followed because it was not practical to employ a load-limiting device for each test condition. As a consequence of this limitation, lumbar forces measured within the Hybrid IIIs actually reached levels considered beyond vertebral fracture levels at the more severe impact levels studied. The related pelvic and thoracic accelerations measured at the more severe pulses are consistent with the "high" lumbar force levels.

Tolerance levels for the three manikins employed during this test series were 1940 pounds (5th ATD = 160 pounds), 2170 pounds (50th ATD = 180 pounds), and 2500 pounds (95th ATD = 210 pounds), respectively. Clearly, even the the 5th percentile male ATD would not have complied with the tolerance criterion under the higher impulse severity levels (i.e., 20 and 30 Gpk). Similarly, the 50th percentile ATD would not have met the criterion at the upper impact severity levels without some means of load limiting. The above results are explained by the selection of test impact parameters and are essentially in agreement with the performance of standard non-energy absorbing seat designs. However, the response of the 95th percentile ATD presented misleading results, indicating compliance at the less severe impact severities. As previously indicated, this is directly related to the nonproportional mass of the 95th aerospace ATD's upper torso.

The rationale to support use of a lumbar force criterion for ejection seats is based on the similarity of lumbar spinal injury mechanisms associated with the two acceleration-time profiles. The inertial loading vector to the aviator's spine is essentially similar whether ejected under accelerative forces or decelerated to zero velocity in a vertical crash scenario. Historically, crash resistant seats have been designed to essentially the same injury tolerance criteria applied to ejection seats (i.e., Eiband Curve and DRI). Since lumbar injuries are directly related to the ultimate strength of spinal vertebrae, a lumbar force criterion appears valid for both seat applications.

CONCLUSIONS

The analysis performed on the test data supports the following conclusions:

1. The Hybrid III anthropometric test device (ATD) in the 5th and 50th percentile sizes can be used as a test surrogate during "vertically-oriented" (i.e., along spinal axis of occupant) impact tests. This conclusion is related to the "straight" spinal segment of the Hybrid III ATD aerospace configuration.

2. The 95th-percentile ATD selected for this investigation exhibited a nonproportional upper torso weight distribution which resulted in lumbar load response levels below those of the 50th-percentile manikin. The 5th percentile male ATD's response appeared commensurately below that of the 50th percentile male ATD.

3. Lumbar force provides a suitable spinal injury measurement within the Hybrid III ATD for comparative analysis of manikin response during evaluation of military crash resistant seat systems and ejection seat systems. Lumbar force can serve as an additional injury parameter in the assessment of spinal injury prediction, supporting the current indicators, such as the Eiband Curve and the Dynamic Response Index (DRI). Assessment of lumbar force data in this test series would have indicated the potential for spinal injury had the test seat employed been under evaluation. However, as noted this result is related to the expedient use of a nonstroking seat mechanism in a severe crash impact environment. Current crash resistant seat designs employ load-limiting mechanisms to manage the seat occupant's response to vertical impacts at the severity levels employed.

4. The abdominal inserts provide an alternate load path to the spinal column of the Hybrid III ATD and can attenuate the level of lumbar force measured by the lumbar load cell. The effect of the abdominal insert was shown to be statistically significant, but no attempt was made to quantify the unloading effect relative to manikin size. The analysis identified the existence of this alternate load path in each of the three manikins tested. Although these data show that the abdominal inserts affected lumbar load response, calibration test methods could be employed to quantify the effect, thus permitting the use of lumbar force as an effective comparative criterion for assessing the potential for spinal injury.

5. All three independent variables had a significant effect on lumbar load. Lumbar loads as measured within the Hybrid III ATD were responsive to the peak acceleration level and velocity change parameters of the crash pulse, and manikin size. The analysis of variance determined that a three-way interaction existed between manikin size, velocity change, and sled peak acceleration (F = 6.27, p = .000).

6. The effect of upper torso restraint was studied and found to have a statistically significant effect on lumbar load. However, the effect was minimal for the 5th and 50th percentile ATDs, i.e., approximately, a 100 pound difference between the mean levels.

RECOMMENDATIONS

1. Lumbar force measurements are recommended as a spinal injury assessment criterion, both for crash resistant seats and ejection seats.

2. A configuration study should be conducted to determine the variance of the 95th percentile aerospace ATD's upper torso mass within the Navy's inventory of test dummies.

3. To support use of a lumbar force criterion, additional calibration testing of both the "aerospace" and "automotive" versions of Hybrid III ATDs should be conducted to assess the following factors:

   a. Response of the 5th percentile female aerospace Hybrid III ATD.

   b. Effect of the "curved" automotive lumbar spinal element on lumbar force.

   c. Repeatability (i.e., similarity of results of a single ATD under identical test conditions) and reproducibility (i.e., variability between ATDs) coefficients should be established for the + Gz headward loading direction.

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BIOGRAPHIES

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