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DYNAMIC PRELOAD AS AN IMPACT PROTECTION CONCEPT

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INTRODUCTION Dynamic preload is defined as an imposed acceleration preceding, continuous with, and in the same direction as an impact acceleration pulse. Some impact accelerations occur with little or no dynamic preload, as in the case of a car moving at constant velocity until crashing into a barrier. Other impact accelerations are accompanied by a variable amount of dynamic preload, as in the case of a car with the brakes applied before striking the same barrier. Dynamic preload should not be confused with static preload, as might be applied by pretensioning a harness restraint system. Static preload has been demonstrated to be useful, and the effects are interrelated, but dynamic preload produces additional effects not attainable through the use of harness tension.

In the conduct of experimental impact testing, facilities may have been used which vary in the dynamic preload they impose. Early impact sled tests used rocket thrust to accelerate a sled to a desired velocity. The sled then coasted into some form of mechanical or hydraulic braking device which applied the retarding force necessary for the planned impact. During the coast phase, however, retarding forces were already at work in the form of wind resistance and rail friction. These forces generally produced sled accelerations in excess of 1.5 G's, sometimes reaching 15 G's. The higher levels of imposed dynamic preload often produced dramatic impact responses in the human occupants of the sled, well before contact with the brake was made. Other impact facilities have been designed to produce impact acceleration from a standing start. The dynamic preload in these cases is always zero. Therefore, the impact acceleration-time curve for two facilities may be identical, but the acceleration-time history prior to the event may differ greatly. The effect of varying the acceleration-time history preceding the impact event is the subject of the present inquiry.

The effect of dynamic preload in previous impact data, and a basis for anticipating protective applications, was defined by Raddin in 1980 to the Aerospace Medical Association. Hearon, Brinkley, and Raddin presented human data, using a decelerator with two levels of preload, to the same group in 1981. The current paper presents results of matched human impact exposures on a decelerator (preload of approximately 0.3 G) and an accelerator (no preload). Before presenting the experimental data, the historical data base will first be briefly reviewed to establish the basis for the current investigation.

TOLERANCE DATA Data gathered in the attempt to explore human tolerance limits are derived primarily from deceleration experiments. These, of course, involve varying levels of dynamic preload. One of John Paul Stapp's rocket sled exposures, for example, was described as follows:

> "At burnout of the rockets, the subject's head and shoulders were pitched forward abruptly into the harness and firmly pressed against the straps throughout the 1.6 seconds of coasting." (3)

The acceleration-time curve for this run demonstrated a peak dynamic preload greater than 4 G during the coast phase. Significant protective benefits accrue to the subject of such a test since, at the least, the head will not snap forward during the impact, since it has already been thrown forward during the coast. It will, therefore, not experience the usual amplified accelerations. Similarly, other viscoelastic body structures may benefit from the preloading. Previous human experience in $-G_X$ impacts suggests that human tolerance to impact increases with increasing dynamic preload. Similar apparent differences in tolerance, injuries, and response accelerations have been noted with animals and dummies. These differences may also be ascribed to dynamic preload.

Comparison of data derived from different impact test facilities, subjects, and conditions has always been difficult. Similar peak G exposures may have been very different pulse shapes and, therefore, different velocity changes and pulse energy content. Restraint system designs and materials are often not comparable. Subjects differ in size, weight, and response characteristics. In short, if clear distinctions between responses with differing preloads are to be made, great care must be taken to assure that all other sources of response variance are well controlled.

The current study is an attempt to do just that, and to establish deceleration exposures as a special case in human tolerance data. Presumed tolerance information derived from tests with high preload would then require interpretation when applied to exposure situations with no preload. Tolerance scaling techniques would be required. Furthermore, if tolerance increases with preload, means should be sought to intentionally impose preload as a protective technique in impact exposures.

EXPERIMENTAL DESIGN This experiment was intended to provide a controlled comparison of human response in matched impact acceleration profiles on decelerator and accelerator facilities. The comparable tests were matched for velocity change of the impact sled. The impact acceleration profiles were approximate half-sine waveforms. The tests were conducted on the Horizontal Decelerator and the Impulse Accelerator at the Air Force Aerospace Medical Research Laboratory (AFAMRL). The ready availability of these facilities for use in human testing and the extensive base of comparative test data were prime factors in selecting forward facing ($-G_X$) tests for this investigation.

Volunteer subjects came from the AFAMRL Impact Acceleration Stress Panel. All subjects successfully completed a thorough medical screening evaluation, including a USAF Flying Class I physical examination, pulmonary function tests, electroencephalogram, exercise treadmill test and a complete battery of skull, chest and spine x-rays. This screening procedure has been more thoroughly described elsewhere (2). Ongoing informed consent was provided by all subjects throughout the experiment, in accordance with the applicable human use guidelines as defined in Air Force Regulation 169-3.

To minimize the potential for injury to subjects, the tests were conducted at presumed subinjury impact acceleration levels. The experimental design matrix is shown in Table I. The pulses in Test Conditions 1 and 3 were preceded by the minimum dynamic preload (approximately 0.3 G) created by nominal track friction on the decelerator. There was no dynamic preload in Test Conditions 2 and 4. The forces acting on the subjects at these exposure levels are generally sufficient to overcome the forces of voluntary muscle contraction and, therefore, produce a response which is suitable for comparative parametric analysis.

TABLE I. NOMINAL TEST CONDITIONS

Sled Acceleration (G)	8	10
Velocity Change (ft/sec)	27	30
Decelerator	#1	#3
Accelerator	#2	#4

The test seat was designed with conventional USAF crew seat geometry with a seat back angle of 13° aft of vertical and a seat pan inclined 6° above the horizontal. No footrest was provided. The subjects were restrained by a lap belt - double shoulder harness constructed of 1.75 inch wide webbing. Prior to each impact test, the subject was instructed to assume the same body posture, with head against the headrest, hands resting on anterior thighs without upper extremity bracing, and posterior thighs in contact with the seat pan.

The test fixture, restraint harness, and subject were instrumented to obtain pertinent objective data during each test. Measured parameters included impact acceleration of the test sled and seat, impact velocity of the test sled, loads reacted at the seat pan, and loads measured at the restraint harness attachment points. Accelerations at the head and chest of the subject were measured by appropriately mounted triaxial translational accelerometers. Photometric data were obtained by two high-speed (500 fps) motion picture cameras mounted on the test fixture, permitting assessment of body segment displacements during the impact. Subjective data were also obtained by means of a post-test questionnaire designed to assess the subject's impression of each impact event relative to other comparable exposures.

The electronic data were processed by computer and the test results were evaluated using the Wilcoxon paired-replicate rank test (5). This statistical technique was selected to compare the peak values of specific measured parameters and to establish the statistical significance of observed trends in the data. Experimentally measured parameters for each subject were arithmetically compared with the same parameter measured for the same subject in a comparable test condition, in order to establish "pair differences". When a sufficient preponderance of ranked pair differences for a specific parameter changed in the same direction, a trend was established as statistically significant by the Wilcoxon analysis. The 90% confidence level (assuming a two-tailed test) was chosen as the level of statistical significance in this study. This analytical approach established each subject as his own control and thereby reduced the effects of biological variability on the data.

Evaluation of the entire measured acceleration-time histories of head and chest was accomplished by calculated severity indices (1). These single parameters, which were derived by a weighted integral of the acceleration-time function taken over the interval of the impact ($SI=\int a^n(t)\,dt$, where $n=2.5$), were used to compare the overall severities of impact responses.

EXPERIMENTAL RESULTS Data were obtained from 56 matched impact tests (32 at the 8 G level and 24 at the 10 G level). Sixteen subjects (15 males, 1 female) participated in the test program. The means and standard deviations of the measured parameters and the statistically significant trends established by the Wilcoxon analysis at the 90% confidence level are presented in Tables II and III. An * indicates a statistically significant change in the designated parameter.

Tests on the decelerator facility were conducted first. Tests on the Impulse Accelerator were then designed to produce an impact velocity as close as possible to that measured for that subject on the Horizontal Decelerator. Since the profiles were almost identical, velocity matching implied close correspondence in acceleration as well. However, the mean sled acceleration peak for the 8 G tests was 0.18 G higher on the accelerator. This difference was systematic enough to appear as statistically significant in the Wilcoxon analysis. To assure that this test bias was not the basis for the observed differences in subject response, 10 G tests on the accelerator were designed to produce slightly lower velocity changes for each subject than had been observed on the decelerator. Acceleration peaks for the 10 G tests were therefore 0.36 G lower on the accelerator. Similar response differences were still observed.

A statistically significant increase in resultant head acceleration was seen at the 8 G and 10 G test levels in the tests conducted on the accelerator. The magnitudes of these increases were 47% and 31%, respectively. Statistically significant increases were also seen in the head Severity Index, which was increased by 88% and 56%, respectively. Statistically significant increases were observed in resultant chest acceleration and chest Severity Index in 8 G level tests conducted on the accelerator. These acceleration findings are all consistent with the interpretation that human response to impact on decelerator facilities is less severe than response to comparable impacts conducted on accelerators.

Statistically significant increases in resultant shoulder strap loads, lap belt loads, and seat pan loads were observed in the 8 G tests on the accelerator. A statistically significant increase at the 90% confidence level was also seen in the resultant lap belt load at the 10 G level in Condition 4. These findings demonstrate that forces imposed on human subjects in impacts preceded even by a minimal dynamic preload were decreased in comparison to those measured during impacts on accelerators in which the dynamic preload is precisely zero.

DISCUSSION The test results show rather dramatic increase in response to acceleration impacts when compared with response to matched deceleration impacts. The differences in response continue to be statistically significant, in most cases, even when the acceleration event was less severe, as seen in the 10 G comparison. The explanation for these differences can be understood in part by examining the concept of dead space and the nature of viscoelastic systems exposed to impact. In spite of pretensioning, some structures of the human body are poorly supported by the restraint system. In typical systems, these include the head, arms, legs,

TABLE II

SUMMARY OF ELECTRONICALLY MEASURED AND COMPUTED DATA FROM WILCOXON ANALYSIS (8 G)
(Peak values are tabulated for velocity, accelerations and loads.)
(n = 16)

TEST CONDITION	1		2		Significant at 90% Confidence
TEST FACILITY	Decelerator		Accelerator		
	Mean	SD	Mean	SD	
SM SLED ACCELERATION (G)	8.23	0.23	8.41	0.16	*
SLED VELOCITY (ft/sec)	27.6	0.36	27.6	0.41	
CHEST ACCELERATION (G)					
-X axis	-9.58	0.79	-9.98	1.23	
+Z axis	6.47	1.09	9.17	4.34	*
Resultant	10.8	0.70	12.5	2.97	*
CHEST SEVERITY INDEX	20.8	2.70	26.0	6.53	*
HEAD ACCELERATION (G)					
-X axis	-10.3	2.29	-14.0	3.29	*
-Z axis	-4.85	2.59	-10.6	2.57	*
Resultant	11.4	2.82	16.8	3.31	*
HEAD SEVERITY INDEX	27.0	9.97	50.8	16.0	*
STRAP LOADS (lb)					
Total Shoulder Straps	535	86	577	102	*
Total Lap Belt	1280	183	1440	239	*
SEAT PAN LOADS (lb)					
+Z axis	1130	224	1220	236	*
Resultant	1190	225	1260	235	*

TABLE III

SUMMARY OF ELECTRONICALLY MEASURED AND COMPUTED DATA FROM WILCOXON ANALYSIS (10 G)
(Peak values are tabulated for velocity, accelerations and loads.)
(n = 12)

TEST CONDITION	3		4		Significant at 90% Confidence
TEST FACILITY	Decelerator		Accelerator		
	Mean	SD	Mean	SD	
SM SLED ACCELERATION (G)	9.91	0.19	9.55	0.22	*
SLED VELOCITY (ft/sec)	30.5	0.34	30.4	0.50	
CHEST ACCELERATION (G)					
-X axis	-12.2	1.32	-11.7	1.51	
+Z axis	7.46	0.91	10.3	4.17	*
Resultant	13.3	0.96	14.2	2.70	
CHEST SEVERITY INDEX	31.2	3.33	33.5	6.33	
HEAD ACCELERATION (G)					
-X axis	-12.2	2.42	-15.0	2.70	*
-Z axis	-7.15	3.67	-11.5	2.72	*
Resultant	14.0	3.76	18.4	3.32	*
HEAD SEVERITY INDEX	41.6	17.4	64.8	17.6	*
STRAP LOADS (lb)					
Total Shoulder Straps	676	116	665	99	
Total Lap Belt	1590	167	1680	246	*
SEAT PAN LOADS (lb)					
+Z axis	1330	198	1410	193	*
Resultant	1390	201	1460	193	

and various internal organs. These structures often must displace before direct accelerating forces can be applied through joints, attachments, or direct contact. This amounts to a functional "dead space", which effectively delays the onset of acceleration and implies an eventual increased magnitude of acceleration to allow the late-starting member to "catch up". A dead space mechanism such as this is more observable externally in tests with high dynamic preload, such as some reported by Stapp, in which the head and extremeties are actually thrown forward during application of preload. In the tests reported here, the dead space mechanism would be less observable and of lower magnitude, but still may occur internally.

Of greater significance in these tests are the modified initial conditions imposed on the viscoelastic system of subject, support, and restraint by dynamic preloading. The initial conditions are observably different in the two cases presented. In the deceleration tests, loads in harnesses and forces on the structure changed during the transition from launch to coast. At impact, therefore, the viscoelastic response of the subject had already begun. Portions of the subject respond to impact partially as springs, and these springs had already begun to displace while under dynamic preload. Such anticipatory displacement as an effect similar to that of removing dead space in the sense that the subject response can follow the acceleration of the supporting structure more closely. However, unlike dead space, which has no spring constant, viscoelastic deformation must take place under dynamic internal loads. These cannot be produced in many cases by static pretensioning of harness systems.

The apparent protective effects of dynamic preload have two significant implications. The first is that our assumptions about human tolerance should be re-examined. The ability of a human to tolerate a high-energy 45 G impact with significant dynamic preload does not imply that similarly capable subjects can tolerate a similar impact without preload. The acceleration-time history prior to the impact must be specified and scaling laws must be devised. The second implication of these results is more positive. If dynamic preload makes impact more tolerable, it should be exploitable in impact protection systems.

Practical utilization of dynamic preload requires anticipation of the impact. In these data, preload was applied over a period of about 3 seconds of coasting, and took place as a consequence of the test equipment characteristics. For practical impact protection, shorter durations of preload would be required, along with a means to impose it in coordination with the impact. Unplanned impacts, such as crashes, would require impact initiation sensors at the vehicle periphery or beyond it. Planned impacts, such as ejection seat firing, could use preload during the pre-ejection sequence. For either case, the minimum duration of a protective preload pulse must still be determined. The optimum magnitude and duration will depend upon the frequency response of the subject and restraint system, and the impact to be experienced.

Work at AFAMRL is continuing in order to define practical applications of dynamic preload for use in aircraft escape systems. This application is particularly attractive, since idealized preloading pulses have also been shown to promise improvement in the displacement-time performance of the seat (4). The potential for practical and realizable systems will be defined by measuring human response to various characteristic preloading waveforms in vertical impact.

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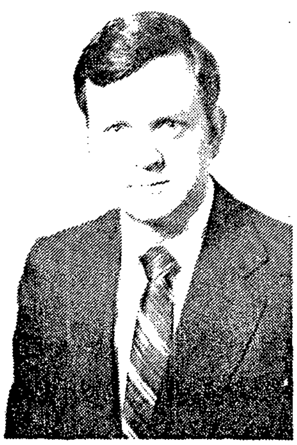
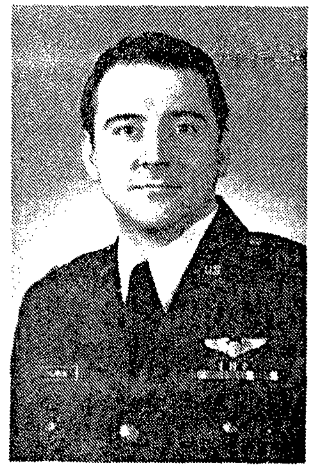
BIOGRAPHIES

Lieutenant Colonel James H. Raddin, Jr. *is a physician-engineer who has served as the Chief Aeromedical Advisor to the Life Support System Program Office of the Aeronautical Systems Division at Wright-Patterson AFB from July 1980 to June 1982. He received a B.S. degree in Aeronautics and Astronautics from the Massachusetts Institute of Technology (MIT) in 1967 and an M.D. degree from the University of New Mexico School of Medicine in 1975. Currently, he is pursuing a Sloan Fellowship in Management Sciences at MIT as part of the USAF residence training program in Aerospace Medicine. Dr. Raddin, Air Force Systems Command Flight Surgeon of the Year in 1977, formalized the concept of dynamic preload during his tenure as a research scientist at the Air Force Aerospace Medical Research Laboratory of the Aerospace Medical Division at Wright-Patterson AFB from 1977 to 1980.*



Lt. Col. James H. Raddin, Jr.

Major Bernard F. Hearon *is also a flight surgeon-engineer. He received a B.S. degree in Aerospace Engineering from the University of Notre Dame in 1973, a Master of Medical Sciences degree from the College of Medicine and Dentistry of New Jersey - Rutgers Medical School in 1975, and an M.D. degree from Tufts University School of Medicine in 1977. Dr. Hearon, currently assigned to the Air Force Aerospace Medical Research Laboratory, has been responsible for conducting human impact experiments designed to investigate the concept of dynamic preload. He and Dr. Raddin have also published a number of technical reports and articles on the F-111 ejection experience and on human impact tests designed to evaluate the F-111 restraint system.*



Major Bernard F. Hearon

LOOK FOR MORE TROUBLES

Be thankful for the troubles of your job. They provide about half your income. Because if it were not for the things that go wrong, the difficult people you have to deal with, and the problems and unpleasantness of your working day, someone could be found to handle your job for half of what you are being paid.

It takes intelligence, resourcefulness, patience, tact and courage to meet the troubles of any job. That is why you hold your present job. And it may be the reason you aren't holding down an even bigger one.

If all of us would start to look for more troubles, and learn to handle them cheerfully and with good judgment, as opportunities rather than irritations, we would find ourselves getting ahead at a surprising rate. For it is a fact that there are plenty of big jobs waiting for men and women who aren't afraid of the trouble connected with them.

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