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TWENTY-FIRST STAPP CAR CRASH CONFERENCE

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Abstract

A series of human volunteer experiments has been conducted to measure the inertial response of the head and the first thoracic vertebra (T_1) to +Gy whole body impact acceleration; that is, acceleration applied to the subject from right to left. The 12-inch HYGE ® accelerator, instrumentation system and procedures were identical to those used for measuring the response to -Gx impact acceleration, previously reported.

Three categories of sled acceleration profile were used: high onset, long duration from 2G to 7.5G with end stroke sled velocity limit of 6.5 meters/sec; low onset, long duration with the same peak acceleration and velocity limits; and high onset, short duration from 5G to 11G. Comparison time profiles of angular acceleration, angular velocity and linear resultant acceleration at the head anatomical origin and horizontal linear acceleration at the T_1 origin are presented at selected peak sled acceleration levels for 5 subjects of various anthropometric dimensions.

Statistical and analytical modeling efforts from this data base are compared with similar efforts for previously reported -Gx experiments.

WEIS, ET AL, CONDUCTED a number of human exposures to -Gy acceleration using a vertical drop tower on which a rigid vehicle was mounted and executed a series of drops using a "non-extensible chest and pelvic harness in the sitting position" in which vector direction was changed by rotating and then re-affixing the vehicle (1).* Instrumentation was not mounted on the man. Heavy torso restraint included a contoured couch in some experiments and a vest in others. A full-coverage helmet was worn for all tests, but after a few initial tests, was tied to the vehicle so that no helmet dynamic response relative to the chair was possible, although it allowed a limited head response relative to the helmet. In this condition of rigid restraint, sixteen exposures using a contoured couch in the -Gy vector, reaching as high as 21.5 -Gy with a rate of onset of 1190 G/sec with total duration of 37 ms and a velocity change of 6.04 m/sec, showed that no structural tolerance limit was reached.

Using an omnidirectional vehicle on 6 volunteers with similar heavy restraints, peak vehicular acceleration of 23.1 -Gy, with rate of onset of 980 G/sec and total time duration of 63 ms, with a velocity change of 7.99 m/sec also showed that no structural, physiological or neurophysiological tolerance limit was attained (1).

Sonntag, in a series of experiments on individuals with heavy lap and torso restraints, but without head-neck restraint, gave volunteers lateral impact accelerations of 9 to 10 -Gy (sled) without injury (2). The seat was instrumented and no ± Gx or ± Gz accelerations were produced. No man-mounted accelerometers were used.

Stapp and Taylor used human volunteers instrumented with a single triaxial accelerometer mounted on the chest in a series of exposures to lateral acceleration up to 24 ± Gy without voluntary tolerance limits being reached (3). However, in these runs the subjects wore a Mercury astronaut helmet on a neck ring attached to a nylon vest and held by a strap passing through the crotch. In addition, side panels were extended on each side of the head-rest (4).

Zaborowski conducted experiments on human volunteers in the lateral vector (-Gy) with unrestrained head and neck (5).

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*Numbers in parentheses designate References at end of paper.

In these experiments, the subject, while restrained in a seat by lap belt and shoulder harness, was accelerated in the +Gy vector until a constant velocity was attained, then was decelerated by a programmable braking system in the -Gy vector. Inertial instrumentation consisted of a triaxial accelerometer strapped tightly to the sternum and a triaxial pack of accelerometers strapped over the right temporal region of the head. Five series of runs were scheduled with 20 tests accomplished at 4G, 20 at 6G, 25 at 8G, 20 at 10G and 2 at 12G levels. Time duration for these exposures ranged from 220 ms for 4G to approximately 50 ms at 12G. (Table 1)

These experiments ceased when a subject suffered a marked decrease in blood pressure and heart rate following a 12G run. Approximately one minute post run, the subject fainted in his seat and his blood pressure could not be detected. Pulse rate was measured at 20-30 beats/min. Within 5 minutes of being laid down in a supine position, the subject fully recovered but complained of impingement of the left shoulder strap on the left side of the neck (5).

Several points can be made about these experiments:

a. Sled velocity change was relatively constant.

b. From the data presented, it is difficult to separate the effects of changes in peak sled acceleration from those of changes in sled rate of onset.

c. The head-mounted instrumentation system was inadequate to measure angular acceleration or velocity.

d. Sled peak acceleration was amplified on the head presumably at the right temporal attachment location by a factor of roughly 2:1 throughout all sled acceleration levels. However, there was no attempt to transfer these data to a standardized head anatomical coordinate system.

A previous study by Zaborowski used lap belt restraint only (6). The vector direction was -Gy induced as noted previously. The seat was an ejection seat with a padded restraint plate applied to the left side at a 30 percent angle from the vertical, in order to prevent lateral motion of the torso beyond this angle, which was believed to be the maximun angle allowable of lateral spinal flexion without injury. Subject-mounted instrumentation was the same as noted previously.

None of the aforementioned studies provide the input-output data required for precise mathematical modeling or design and/or validation of a dummy.

Table 1 - -Gy Acceleration Effects on Man (after Zaborowski) (5)

Average	Peak Sled Velocity (m/s)	Peak Sled (G)	Peak Sled Onset (G/sec)	Acceleration Head (G)
4G	4.21	4.47	228.6	7.1
6G	4.49	6.64	363.2	10.1
8G	4.49	8.80	429.9	15.0
10G	4.20	10.56	408.2	19.9
12G	4.25	11.59	1088.5	21.7

PURPOSE

The Naval Aerospace Medical Research Laboratory Detachment (NAMRL Detachment), New Orleans, Louisiana, is conducting a continuing program to determine the dynamic response of volunteer subjects to impact acceleration (7, 8, 9, 10). The effect of duration and onset of -Gx acceleration runs has been reported (11).

The specific purpose of this paper is to present the effect of sled profile parameters (peak sled acceleration, onset and duration) on the dynamic response of the head and neck for +Gy acceleration profiles and to compare these results with the similar study for the -Gx data base.

METHODS

EXPERIMENTAL DESIGN - Five human volunteer subjects* were exposed to +Gy sled acceleration profiles with peak sled accelerations from 2 to 11G in 1G increments. The sled acceleration profile is characterized by the peak sled acceleration, the rate of onset during the rising portion of the acceleration profile and the duration of time spent at acceleration levels above 75 percent of peak sled acceleration. Each subject was run with a sled profile characterized by a high rate of onset and long duration (HOLD), a high rate of onset and short duration (HOSD) and a low rate of onset and long duration (LOLD). More specifically, the HOLD condition from 2 to 7G, the HOSD condition from 5 to 11G and LOLD condition from 3 to 7G were examined in this study.

SLED ACCELERATION PROFILES - A Bendix HYGE ® pneumatically driven .3048m diameter accelerator was used to accelerate an approximately 1.2m by 3.7m sled of 1669 kg mass which was rail mounted on twelve Delrin AF ® pucks. The acceleration stroke is limited to 1.52m and sled mounted brakes were not used. The effective drag is about .2G and the sled was allowed to coast to a stop. Total rail length is 213m. The subject was restrained in a nominally upright position by shoulder straps, a lap belt and an inverted V pelvis strap tied to the lap belt. A loose safety belt around the chest was also

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* Anthropometric data on the five subjects used in the study had been measured but was not available at the time of this writing.

employed. The thrust vector of the sled was nominally directed from the right to the left shoulder and the subject was positioned snugly against a slightly padded wooden board used to limit the upper torso motion (Figure 1). The initial position of the subject's head and neck was approximately the same as that used for the -Gx study and the neck-up/chin-up initial condition (10).

The average values and standard deviations of the pertinent sled parameters are shown in Table 1. Rate of onset is defined as the slope on the rising portion of the acceleration profile between 10 and 90 percent of peak sled acceleration and duration is defined as the time spent above 90 percent of peak sled acceleration. The stroke [illegible] integration of the sled profile and for a given G level correlates with duration. Figure 2 shows the sled acceleration profiles for each condition defined by onset and duration averaged over subjects at 7G. The sled profiles are controlled very closely (Table II) and the comparison at other G levels would be similar.

EXPERIMENTAL MEASUREMENTS - The dynamic parameters of interest presented in this paper were derived from measurements using six piezoresistive accelerometers mounted on a T shaped plate at the mouth and six accelerometers mounted on a T-plate at the spinous process of the first thoracic vertebral body (T1). The configuration of the accelerometers on the T-plate and the error propagations associated with this method for determining linear displacement, velocity, acceleration and angular orientation, angular velocity and angular acceleration components of a rigid body have been described previously (12). The cinephotographic system (13) and two rate gyroscopes were used to validate this measurement system.

In order to compare subjects at similar points in the anatomy, it is required to define a head anatomical coordinate system and a T1 anatomical coordinate system (10, 14). These anthropometric coordinate systems are related to the instrumentation coordinate systems by three dimensional x-ray anthropometry for each subject (10).

The basic reference frame for the entire series of experiments is fixed to the laboratory. This is established by first defining a sled coordinate system, in which the origin is a benchmark permanently machined into the sled structure. The +X axis is parallel but in the opposite direction to the thrust vector of the accelerator. The +Z axis is parallel to gravity and positive upward and the +Y axis is established so that the XYZ axes form an

Fig. 14 - First motion of sled

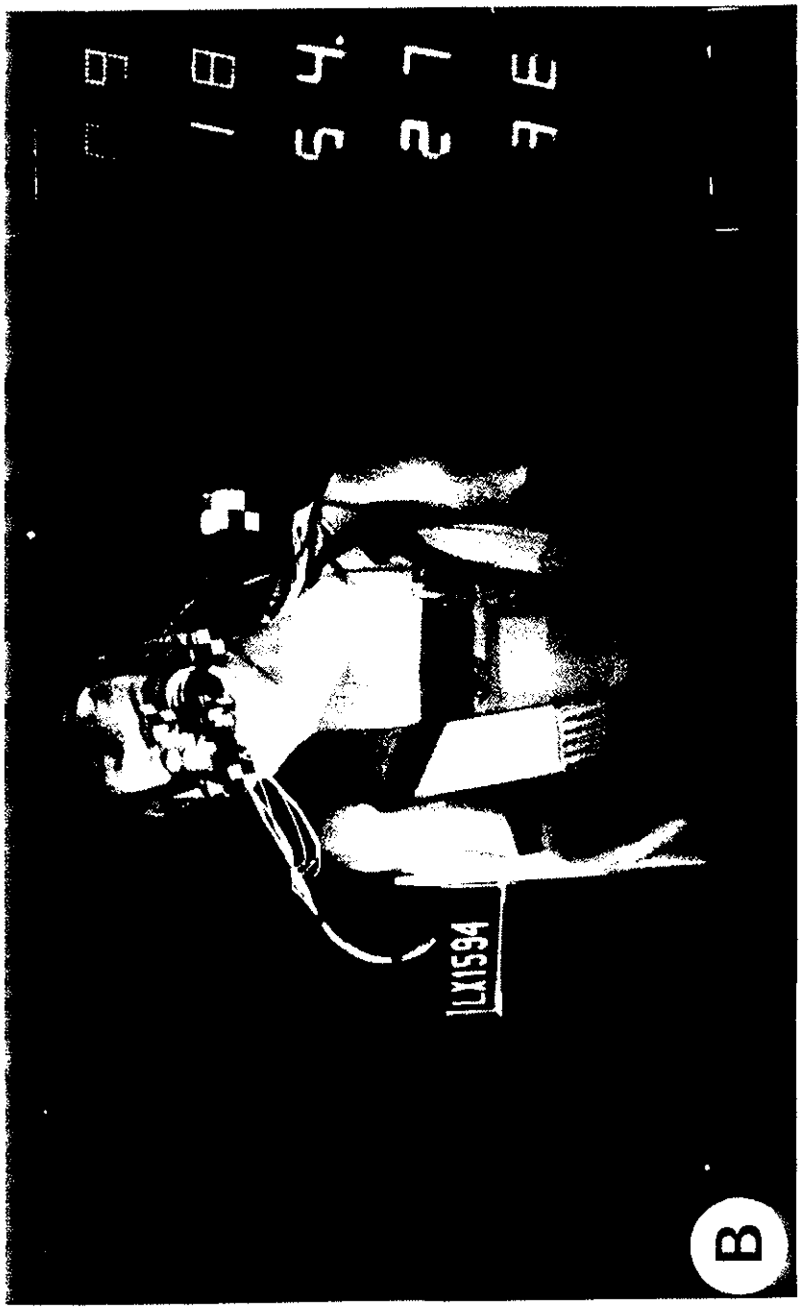


Fig. 1B - Peak head angular acceleration

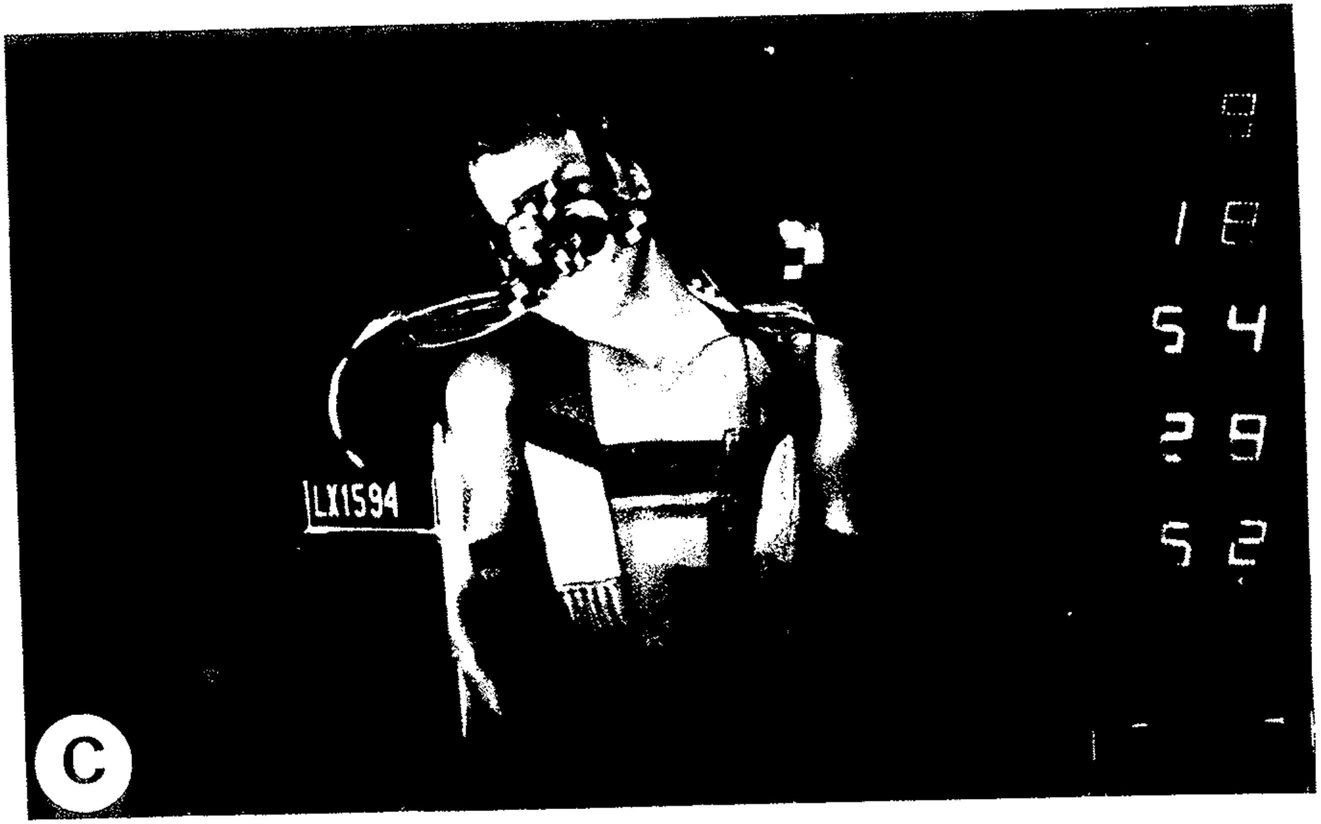


Fig. 1C - Maximum head angular velocity

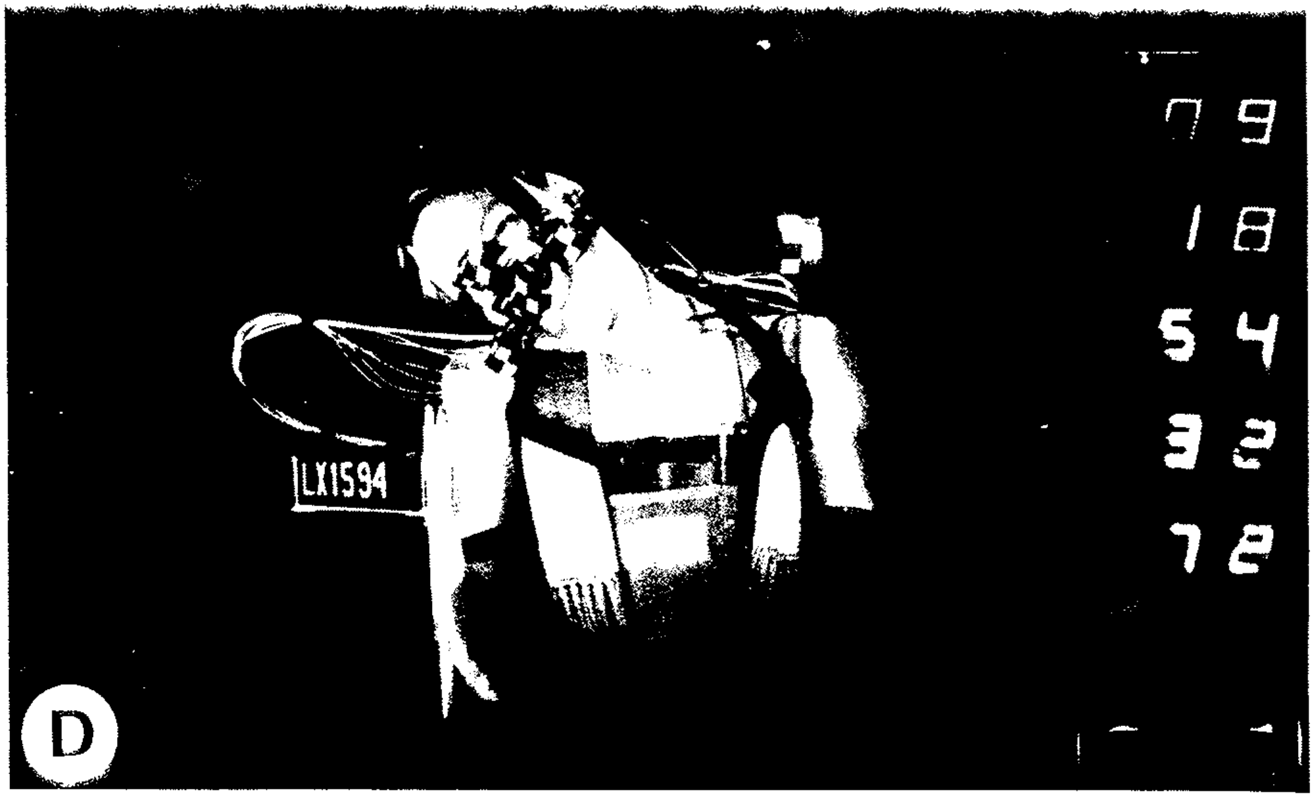


Fig. 1D - Maximum head angular displacement

Table II Summary of Average and Standard Deviations of Parameters of Interest (All G levels and conditions)

ENTRY = Average
Standard Deviations

NOMINAL G LEVEL	RUN NUMBERS IN AVERAGE, EX	COND	PEAK SLED ACCEL M/SEC^2	SLED ONSET M/SEC^3	END STROKE VEL M/SEC	SLED DURAT SEC	PEAK HORIZ ACCEL AT T1 M/SEC^2	PEAK HEAD ANG ACCEL RAD/SEC^2	PEAK HEAD ANG VEL RAD/SEC	PEAK HEAD RESULT ACCEL M/SEC^2
2	1446, 1617, 1620 1767, 1768	[illegible]	21 400 330	1433 800 48 201	6 594 441	.121 010	48 600 5 941	219 000 58 775	8 580 1 329	33.400 2.770
3	1572, 1625, [illegible] 1789, 1791	[illegible]	36 [illegible] 304	[illegible] 000 319 578	6 57[illegible] 111	144 003	75 200 23 328	39[illegible] 000 5[illegible] 019	12 420 1 178	53 800 9 039
3	1883, 1884, [illegible] 188[illegible]	[illegible]	39 650 1 [illegible]	[illegible] 500 81 970	5 682 20	108 002	62 250 13 376	581 000 5[illegible] 666	9 250 733	45 125 5 9[illegible]
4	157[illegible], 1628, [illegible] 17[illegible], 1790	[illegible]	51 200 1 052	860 000 202 994	6 596 110	131 003	87 400 13 593	599 000 67 952	16 220 3 575	73 500 14 891
4	[illegible] [illegible]	[illegible]	50 [illegible] 1 400	939 250 153 507	6 592 [illegible]	119 001	87 125 34 025	490 000 166 333	11 800 3 068	75 250 17 928
[illegible]	1514, 1617, [illegible] 1524, 1825	[illegible]	[illegible] 72	5235 200 572 513	6 576 056	100 .002	129 000 20 881	736 000 167 571	19 200 2 619	84 000 9.138
5	1457, 1946, [illegible] 1947, 1944	[illegible]	49 690 952	1092 400 70 974	6 546 092	092 004	117.000 31.281	649 000 115 456	17 860 2 531	96 500 19 084
5	1675, 1665, [illegible] 17[illegible], 1708	[illegible]	49 980 893	5990.000 840.178	2 038 031	036 001	94 500 7 000	553 000 20 498	33 860 1 365	53 200 8 3[illegible]
5	1592, 1649, [illegible] 1912	[illegible]	60 850 1 249	5815 250 1407 324	6.475 .048	090 .001	161.250 16 520	1095 000 139 [illegible]	25 550 2 932	119 250 13 124
6	1534, [illegible] [illegible]	[illegible]	59 650 968	1293 500 45 618	5 630 157	078 003	131.250 17.347	268 000 106 [illegible]	[illegible] 625 3 [illegible]	111 500 [illegible] 295
6	1715, 1676, [illegible] 1714, 1712	[illegible]	61 900 1 085	7255 800 393 722	2 390 025	034 000	148 000 27 386	825 000 121 419	58 680 1 028	[illegible] 600 9 396
7	1503, 1921, [illegible] 1920, 1924	[illegible]	69 400 1 [illegible]	5957 400 5[illegible] 945	6 488 996	080 001	190 600 26 396	1169 000 251 959	[illegible] 3 029	143 800 11 967
7	1510, 1957, [illegible] 1955	[illegible]	70 125 1 [illegible]	[illegible]18 750 64 526	6 415 133	067 .002	149 000 4 546	1078 750 [illegible]	15 425 4 552	135 500 15 610
7	1720, 1690, [illegible] 1781, 1719	[illegible]	70 5[illegible] [illegible]8	8262 000 7[illegible] 975	2 600 [illegible]	003 001	148 000 22 390	905 000 64 [illegible]	20 250 1 246	8 700 9 7[illegible]
8	1730, 1714, [illegible] 1728, 1729	[illegible]	80 0[illegible] 593	10[illegible] 400 10[illegible] 562	2 864 050	032 .001	193 000 50.339	1032 [illegible] 7[illegible]	22 380 597	88 900 16 589
9	1740, 1724, 1725 1738	[illegible]	89 275 1 131	14567 500 2336 049	2 995 [illegible]	031 005	259 500 54.262	1227 500 234 716	25 825 2 486	99 250 20 807
10	1763, 1752, [illegible] 1762, 1764	[illegible]	100 8[illegible] 1 0[illegible]	16409 200 1132 995	3 134 [illegible]	029 000	316 250 43 851	1403 [illegible] 9[illegible] 574	18 380 1 594	109,500 13 883
11	1849, 1853, [illegible] 1854, 1855	[illegible]	108 3[illegible] 1 [illegible]	18525 600	3 274 019	028 003	241 000 16 696	1602 000 215 841	12 080 3 167	115 400 21 824

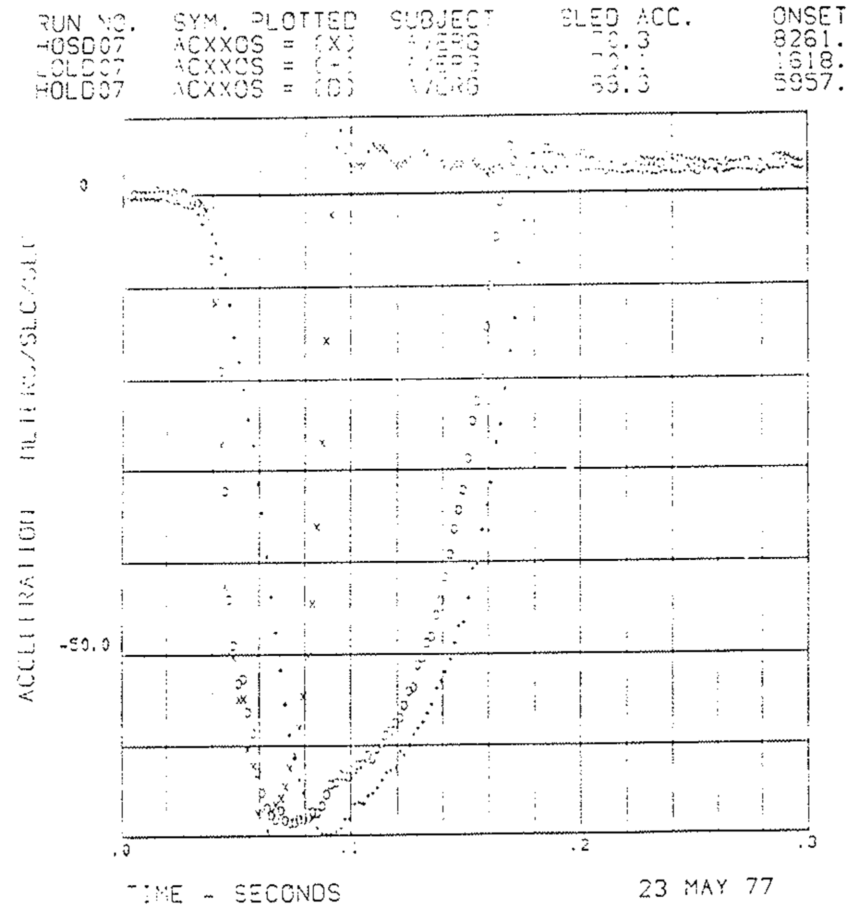


Fig. 2 - Average sled acceleration profile (7G)

orthogonal right hand triad. All coordinate systems used in this study are right handed where X, Y and Z axes are taken in that order. The sled acceleration is in the -X laboratory direction. The orientation of the subject on the sled is such that the sled acceleration is in the +Y anatomical direction. The determination and definition of both the head and neck anatomical coordinate systems are described in Reference 15.

The dependent variables presented in this report are named and defined as follows:

a. RHACXS - Resultant Angular Velocity - is the resultant of the head angular velocity about the head anatomical X and Z axes. The component of angular velocity about the anatomical Y axis (pitching of the head) is not significant for these +Y impact acceleration runs.

b. QHACXS - Resultant Angular Acceleration - is the resultant of the head angular acceleration about the head anatomical X and Z axes. The component of angular acceleration about the anatomical Y axis is not significant for these +Y impact acceleration runs.

c. AAOXOS - Resultant Linear Acceleration - is the magnitude of the head linear acceleration at the origin of the head anatomical coordinate system relative to the laboratory reference coordinate system.

d. ANXXOS - Horizontal acceleration at T_1 is the acceleration component of the T_1 anatomical coordinate system origin relative to the laboratory reference coordinate system along the +X axis of the laboratory reference coordinate system.

e. ACXXOS - Sled acceleration is the acceleration of the sled along the X component of the laboratory coordinate system. The laboratory Y and Z components of acceleration are negligible. All of the recorded data are relative to a zero time established as 40 milliseconds prior to sled first motion as determined from the sled acceleration profile.

f. RANGLE - Direction of angular velocity vector is defined as the arc tangent of the component of head angular velocity about the head anatomical Z axis divided by the head angular velocity about the head anatomical X axis. The component of head angular velocity about the head anatomical Y axis is not significant for these +Y impact runs.

The time on all plots is relative to a time (data processing time zero - DPTZ) established as 40 milliseconds prior to first motion of the sled. First motion of the sled is determined by the best straight line fit to the rising portion of the sled acceleration profile between 20 and 50 percent of peak sled acceleration. The extrapolation of this line to its intercept with the time axis establishes time of first motion.

This study is directed toward the evaluation of the average effects of onset and duration over subjects. The subjects were pooled to obtain average profiles of parameters of interest as well as for purposes of subsequent regression analysis on peak values of interest. The average profile for each variable of interest was calculated for each experimental condition and comparison plots of these average profiles are shown for a peak sled acceleration level of 7G in Figures 3-6. The comparison at other G levels was calculated and would have indicated similar results.

The average profile for each condition was obtained by averaging across subjects using first motion as determined from the sled profile to align the profiles of the subjects. The variations in time at which peak values of head and T_1 response measurements occurred were small enough across subjects so that the average profiles were an excellent summary of the replications.

Table III shows the average standard deviation between profiles averaged in a time window from 80 to 250 milliseconds.

In this study, the relationship of head peak angular acceleration, head peak angular velocity, head peak resultant acceleration and T_1 peak horizontal acceleration to sled onset, duration and peak acceleration were of particular interest.

For each variable of interest, the peaks were read manually from the variable profile. The first positive major peak was used for the parameters of head angular acceleration, angular velocity and resultant linear acceleration. These first peaks were ordinarily found to be the largest for these runs with the exception that the angular acceleration for one subject was characterized by two peaks of almost equal value.

An unambiguous first peak was found to be more difficult to define for the horizontal linear acceleration at T_1. The first peak was always negative and was usually followed by a relatively sharp decrease in magnitude followed by a series of lesser peaks. The first peak was selected as the peak value as long as the decrease subsequent to it was of sufficient magnitude. However, if the decrease was minor and the continuing part of the curve fit in well with its antecedent, the second peak was selected.

The peak values of the parameters of interest were regressed on the three parameters defining the sled profile. A stepwise, multiple linear regression analysis was used in which parameters were eliminated on the basis of an F test if found to be not signi-

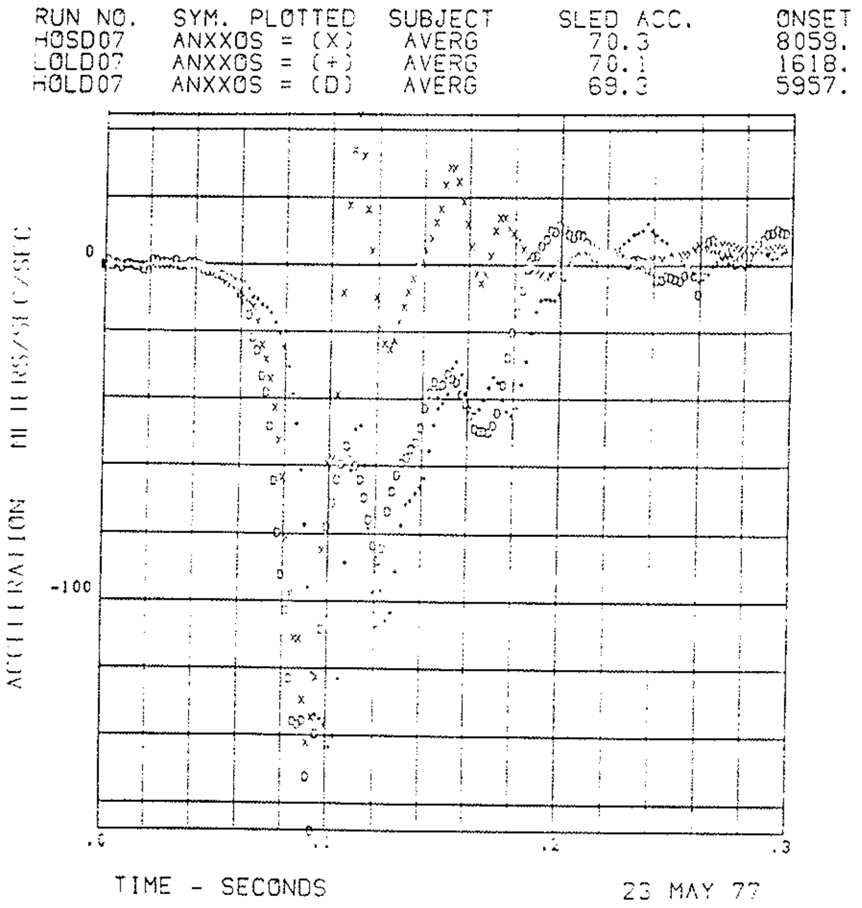


Fig. 3 - Average profiles of horizontal acceleration at T_1 anatomical origin (7G)

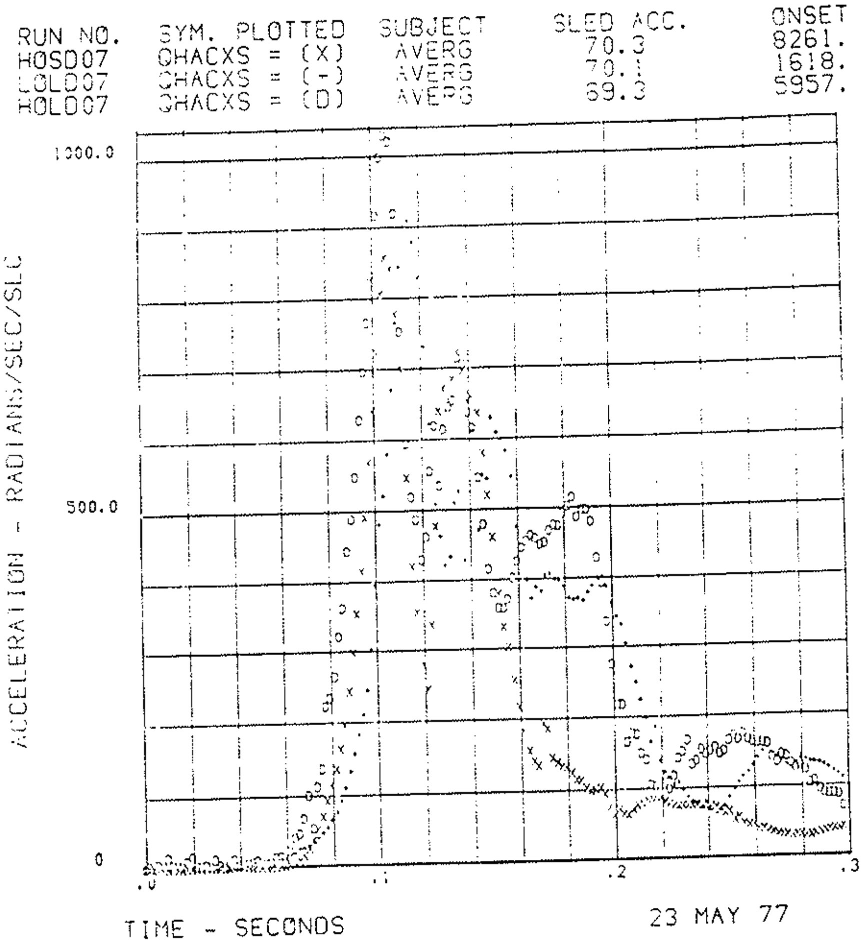


Fig. 4 - Average head angular acceleration profile (7G)

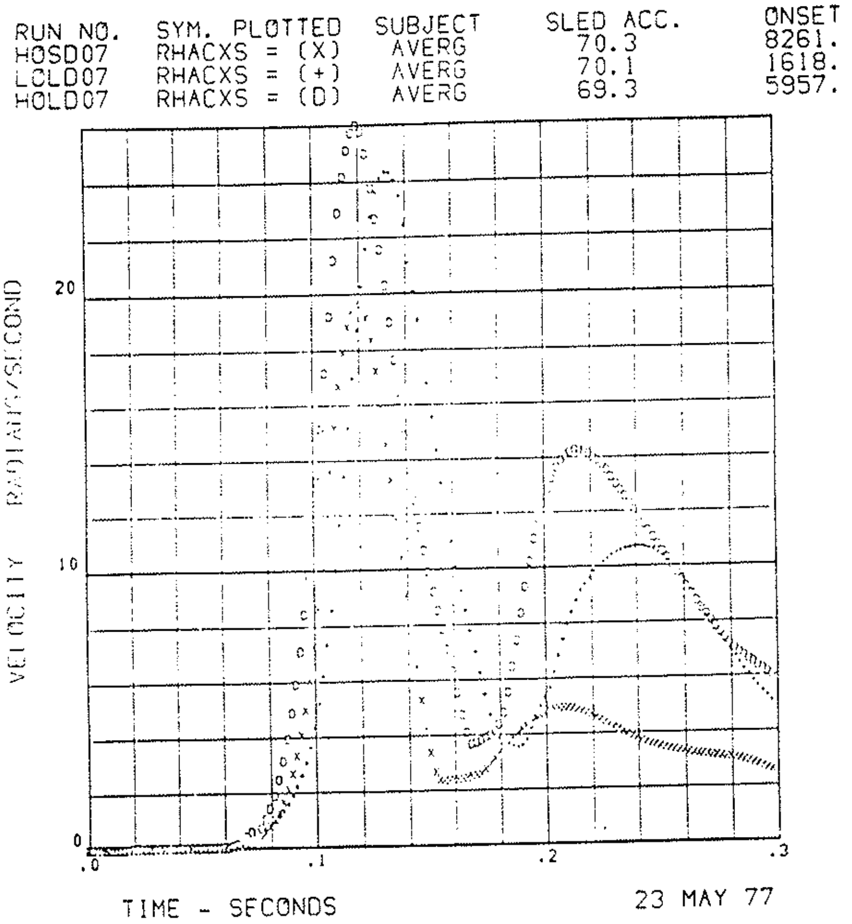


Fig. 5 - Average head angular velocity (7G)

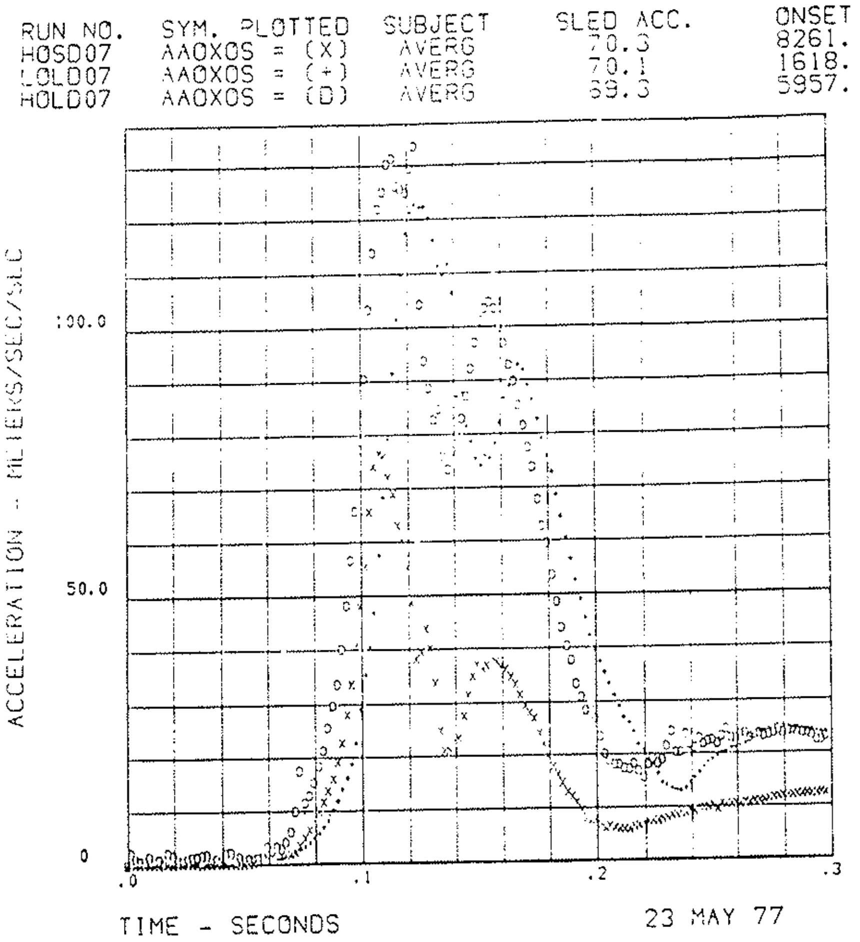


Fig. 6 - Average resultant linear acceleration at head anatomical origin (7G)

ficant at the 5 percent level.

In addition, regression of head kinematic variables on peak horizontal linear acceleration at the T_1 anatomical origin was also obtained. Previous attempts to define equivalent onset and duration parameters for the horizontal acceleration at T_1 were only partially successful and were not attempted in this study.

RESULTS

The 7G average profiles for horizontal acceleration at the T_1 anatomical origin (ANXXOS), resultant head angular acceleration (QHACXS), resultant head angular velocity (RHACXS) and resultant linear acceleration of the head (AAOXOS) are presented in Figures 3 through 6. Each figure shows the comparison of the average profile for the three conditions defined by onset and duration. The profile for each condition was determined by averaging over the subjects. The variability across subjects was evaluated by calculating the average root mean square error in a time window from 80 to 250 milliseconds. Table III shows this error for each variable condition and G level. This time window for the evaluation of the average standard deviation was selected to include the region of interest for all of the output variables without including regions that would have misleadingly reduced the variability

Observation of Figure 3 indicates that the profile structure for horizontal acceleration at T_1 is very similar for each of the conditions. Corresponding peaks can be found for each condition and it is possible that we are observing the impulse response of the restraint torso dynamic system. As to be expected, the latency for the first peak of the LOLD condition is larger when compared to the HOLD or HOSD condition. The delay in the first peak for the LOLD condition relative to that for the HOSD and HOLD condition can be observed in the plots for all the variables (Figures 3 through 6). The magnitude of the HOLD condition is greatest, with little difference between the HOSD and LOLD conditions.

The magnitude of the head angular acceleration for the HOLD condition is greatest with little difference between the HOSD and LOLD condition. The magnitude of the second peaks (maximum angular deceleration) is a large percentage of the magnitude of the first peak and on individual runs is often as great as the first peak. This effect seems to be subject dependent and is most pronounced for one particular subject who was quite short and muscular. Semiquantitatively, the magnitude of the peak head angular

Table III - Root Mean Square Error in Average Profile

(Time Window for RMS was 80-250 MSec)

Var. / G's	ACXXOS M/Sec^2			QHACXS Rad/Sec^2			RHACXS Rad/Sec			ANXXOS M/Sec^2			AAOXOS M/Sec^2		
	HOLD	HOSD	LOLD	HOLD	HOSD	LOLD	HOLD	HOSD	LOLD	HOLD	HOSD	LOLD	HOLD	HOSD	LOLD
2	1.4495			46.6691			1.2711			7.7786			3.4253		
3	.6321		.9981	63.8131		41.824	1.2503		1.0841	8.4709		7.3325	4.8901		4.5856
4	.7944		.8456	80.1707		96.1602	1.3811		1.8633	10.028		12.893	5.9524		8.6168
5	.8932	.6399	.8336	115.409	60.8125	118.853	2.0545	1.1694	2.0577	22.0138	16.6054	15.9196	8.4472	4.9348	9.9497
6	1.5569	.8011	2.1782	137.250	81.4807	159.916	2.4074	1.2313	2.2821	22.5965	16.0341	18.078	10.9471	7.0141	12.4887
7	.9906	.6824	1.1577	179.450	91.0262	186.132	2.8482	1.4404	2.4232	22.2057	15.9796	18.675	13.1767	8.2793	12.6317
8		.8087			82.9429			1.1713			23.2240			9.2385	
9		1.8028			117.552			1.6905			26.9667			10.8080	
10		.7223			149.256			1.6906			32.7761			10.3573	
11		1.0577			191.010			2.5044			37.9990			11.2222	

deceleration (second peak) relative to the peak head angular acceleration (first peak) is greater for +Gy runs than for -Gx runs.

The peak angular velocity for HOLD is the greatest, with the LOLD condition a fairly close second and the HOSD condition significantly less than either of the previous conditions. The resultant head linear acceleration, Figure 6, is a bimodal curve and very similar in structure, independent of onset duration condition. There is little difference in the magnitude of the first peak for HOLD and LOLD conditions, but both are significantly greater than the corresponding peak for the HOSD condition.

Allowing for the fact that in this study resultant head angular acceleration and velocity are presented, instead of the single component of the -Gx study, the profiles for +Gy are very similar to those for -Gx (11).

In Table III, the small error in the sled acceleration variable indicates the excellent control of sled parameters. For all variables, the error increases with G level, but in terms of peak values for that variable is not appreciable. The error for the HOLD and LOLD condition is approximately the same in each of the profiles. The significantly lower error in the HOSD condition may be somewhat misleading because the time window from 80 to 250 milliseconds for this condition is too large and extends into a region where there is little output and consequently indicates small differences across subjects.

In Table II the average values and standard deviations for sled profile parameters and peaks of kinematic output variables of interest are shown at each G level for each condition. The standard deviation in sled profile parameters is in general small in relation to the average value of the parameters at any G level for any condition. The end stroke velocity was limited to approximately 6.5 m/sec and hence the duration for long duration runs varied from .144 seconds at 3G to .090 seconds for 7G runs. The duration for the LOLD runs was significantly less than for the HOLD runs at all G levels. The duration for the HOSD condition decreased with G level varying from .036 to .028 seconds and is much less than either of the long duration conditions.

The rate of onset increases with G level and is the most variable sled parameter. The onset for the low onset condition (LOLD) is significantly less than that for the high onset conditions and in general is less variable across subjects.

All of the output variables (last four entries of Table II) have significant variability across subjects compared to the average peak value.

Figures 7 through 9 are plots of the average peak values for the output variables of Table II. Each plot has the average value for each condition plotted versus peak sled acceleration in (a) and peak horizontal acceleration at T_1 in (b) of Figures 7 through 9. Superimposed on these plots for comparison are the average peak values for the -Gx acceleration vector (11). The dashed line on each curve is the regression line obtained from pooling +Gy data for all subjects and conditions in the peak sled acceleration range from 2 to 8G. Data beyond this point was not used in the regression because many of the curves appeared to require non-linear regression models.

Comparing the peak head angular acceleration versus sled acceleration (Figure 7a) for the +Gy with the -Gx runs, the trend appears about the same but the level is much higher with the +Gy runs independent of sled onset and duration. On the other hand, in Figure 7b, the peak head angular acceleration is plotted versus the T_1 peak horizontal acceleration and the difference between the +Gy and -Gx vectors is much less apparent. The higher head angular accelerations seen in the +Gy study are undoubtedly the result of higher acceleration at T_1 for the same sled acceleration. The coupling of sled forces to the upper torso of the subject through the lightly padded rigid board contact with the subject's right shoulder, as well as the different transmission path through the torso, are responsible for this increased T_1 linear acceleration in the +Gy runs. Figure 10 compares the T_1 horizontal acceleration versus peak sled acceleration for the +Gy and -Gx data base and clearly illustrates the increase in the peak T_1 linear acceleration with the +Gy runs independent of sled onset/duration condition

The instrumentation mount at T_1 is a pressure molded mount applied by a strap system designed to compress the skin over the prominence of the spinous process of the first thoracic vertebral body. Relative motion between the mount and the vertebral body is possible. The redundant measurement system on the mount used for validation of instrumentation cannot be used to resolve the question of the extent of relative motion between the mount and the vertebral body.

However, the restraint of the subject for these +Gy experiments is such as to limit torso motion and hence changes in the geometry of the torso in the T_1 mount region. Observation of the photography does not indicate motion of the mount relative to the torso but this does not preclude the existence of high frequency acceleration spikes.

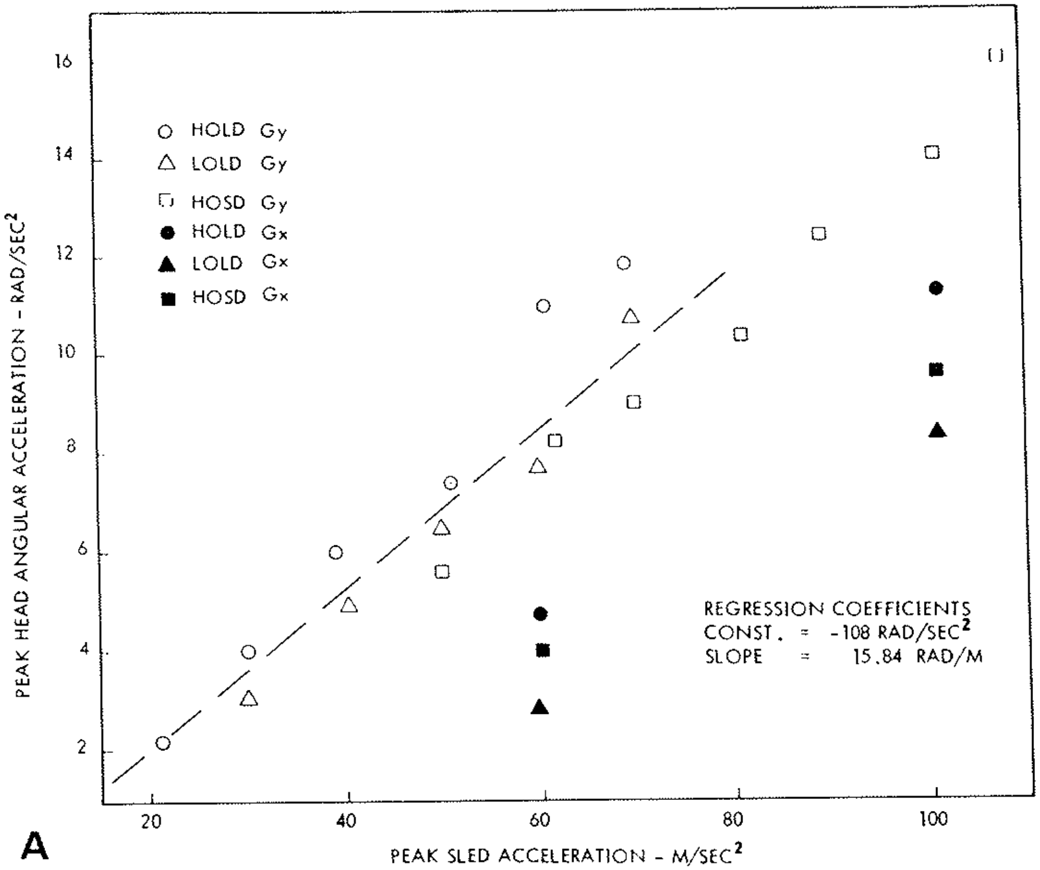


Fig. 7A - Peak head angular acceleration versus peak sled acceleration

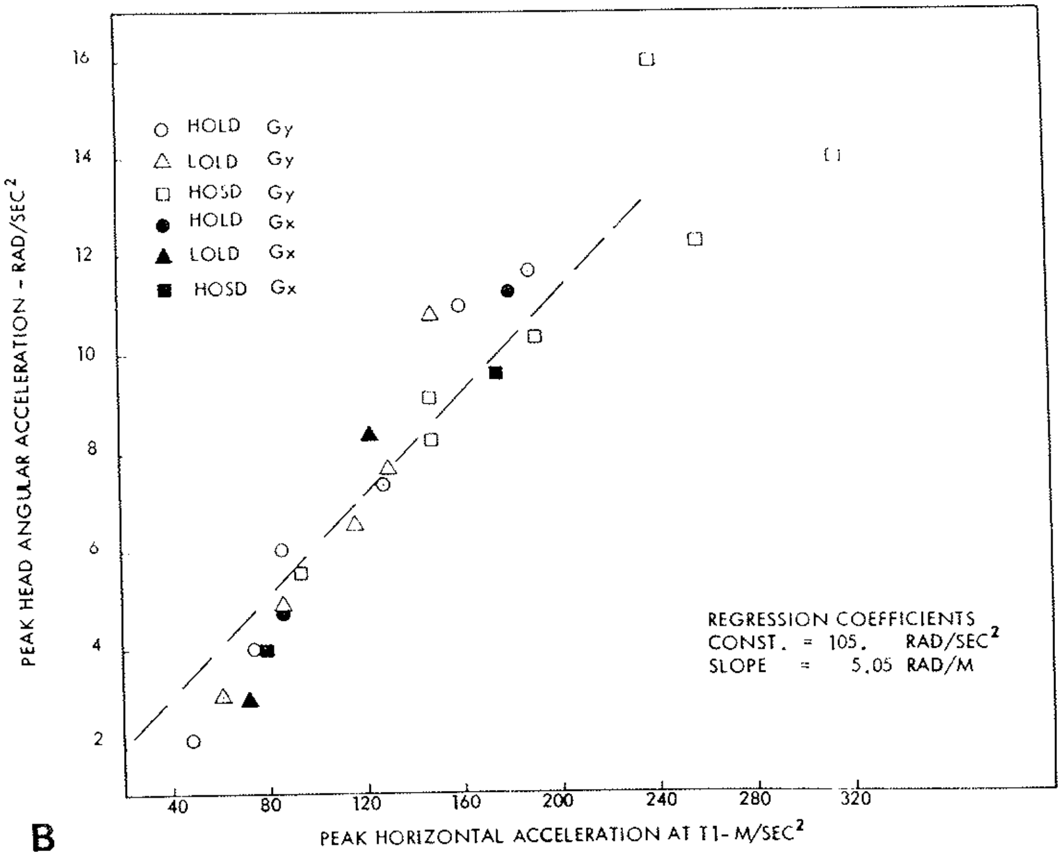


Fig. 7B - Peak head angular acceleration versus peak acceleration at T_1

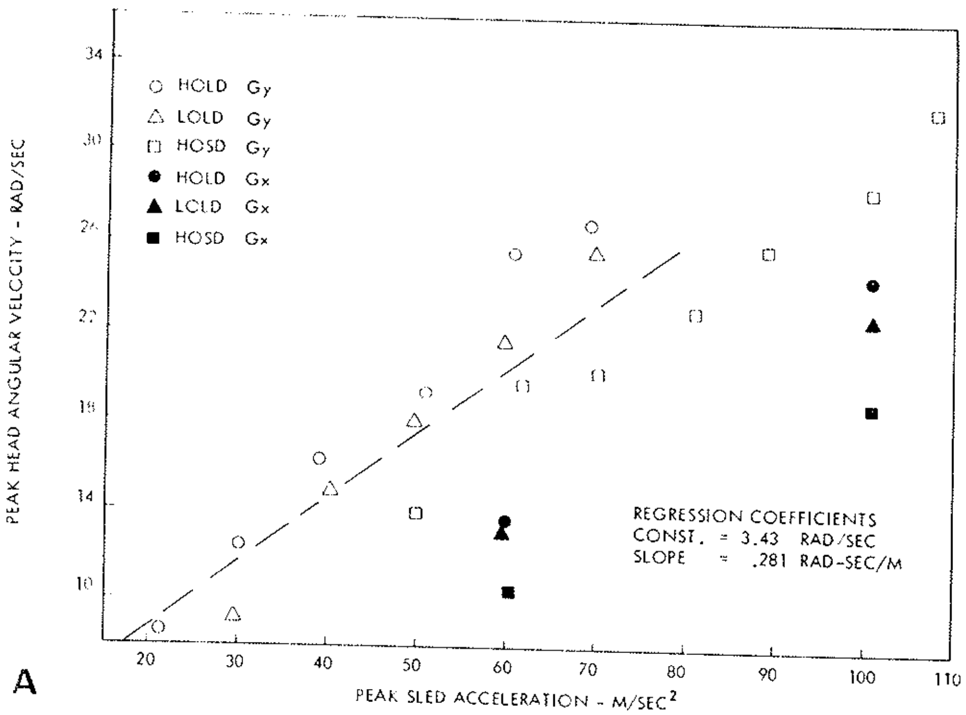


Fig. 8A - Peak head angular velocity versus peak sled acceleration

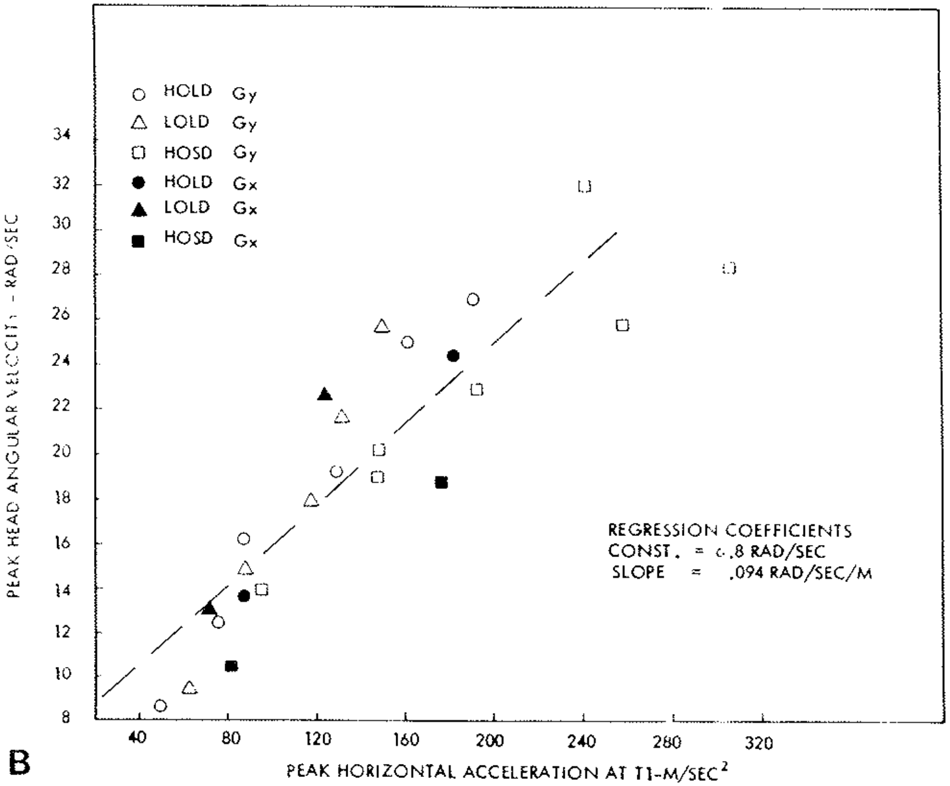


Fig. 8B - Peak head angular velocity versus peak acceleration at T_1

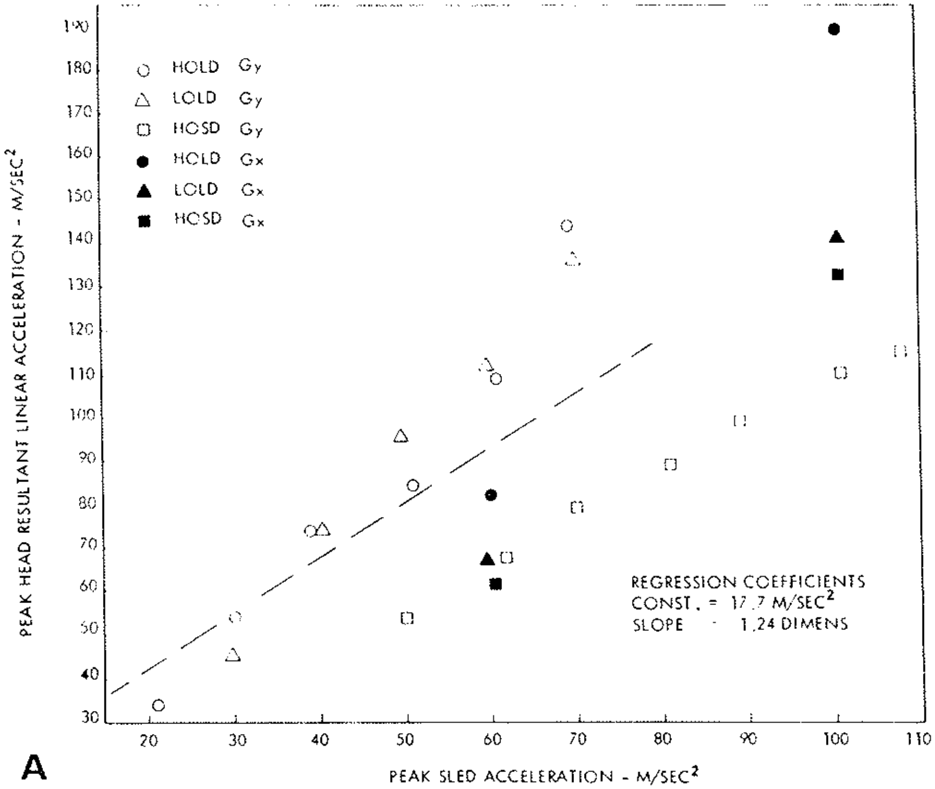
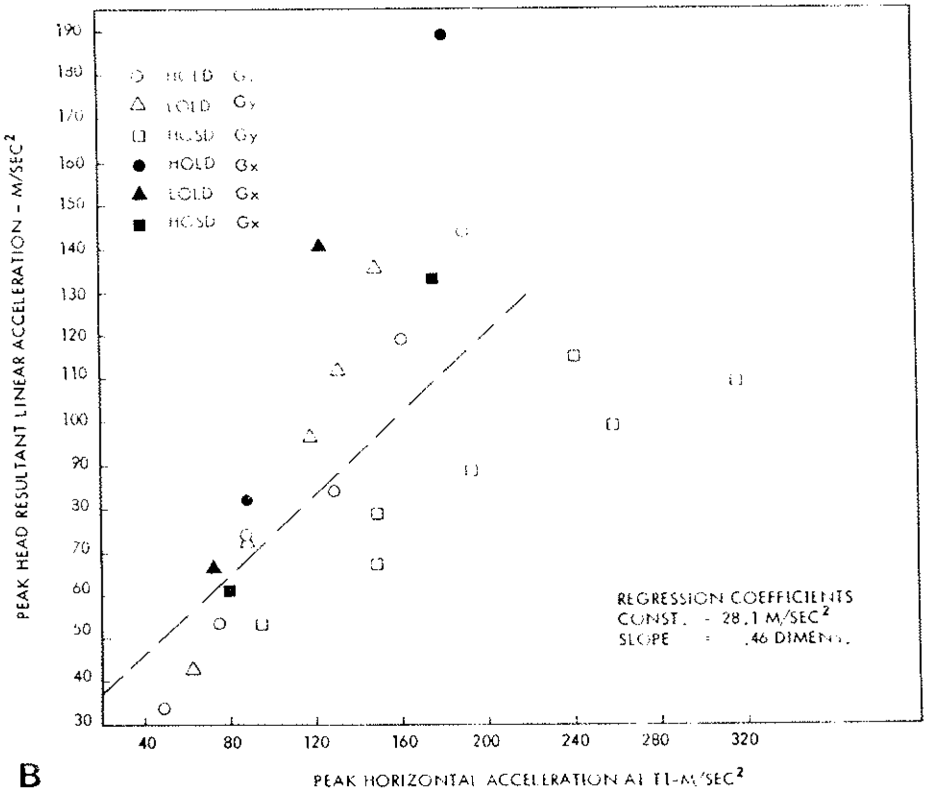


Fig. 9A - Peak resultant linear accelerations of head versus peak sled acceleration



B

Fig. 9B - Peak resultant linear acceleration of the head versus peak horizontal acceleration at T_1

The most convincing arguments that the acceleration observed at T_1 is that of the vertebral body and not artifact is the similarity in profile at T_1 across subjects and the orderly change in the time delay of peak acceleration at T_1 with peak acceleration at the sled. In addition, the ratio of peak acceleration at T_1 to that of the sled is approximately the same at all G levels.

Finally, a similarity for +Gy and -Gx data in the regression of the head angular acceleration on peak accelerations at T_1 in the presence of artifactual T_1 data seems unlikely, since the angular acceleration data was derived from accelerometer data from the mouth mount and is independent of the T_1 measurement system.

Restricting the discussion to the +Gy data base, it also appears from Figure 7b that all the significant effects of sled onset and duration on peak head angular acceleration can be explained by changes in the peak horizontal acceleration at T_1.

Figure 8a is a plot of peak head angular velocity versus peak sled acceleration. Comparing the +Gy and -Gx data, it is observed that the +Gy has a greater angular velocity than the -Gx data independent of condition. Once again, when peak angular velocity is plotted versus peak T_1 horizontal acceleration (Figure 8b), the difference between the two acceleration vectors is much diminished. For the HOLD and LOLD condition, the difference is undetectable, whereas the short duration condition (HOSD) appears to have less angular velocity for both the +Gy and the-Gx runs.

The major determinant of peak angular velocity for the +Gy data base is the peak T_1 horizontal acceleration with a lesser effect due to duration.

Figures 9a and Figure 9b are the plots of the resultant head linear acceleration at the anatomical origin versus peak sled acceleration and peak T_1 horizontal acceleration respectively. For this variable, the peak resultant head linear acceleration viewed as a function of T_1 acceleration reveals that all sled onset/duration conditions for the -Gx runs are in reasonably good agreement with those for HOLD and LOLD +Gy runs. However, the HOSD +Gy runs have a significantly lower magnitude than those of the other two conditions indicating that in this variable there is a larger effect of duration in the +Gy runs than in the -Gx runs.

In Table IV, the coefficients obtained from regression of the dependent variables of interest on the parameters defining the sled acceleration profile for the +Gy data base are presented.

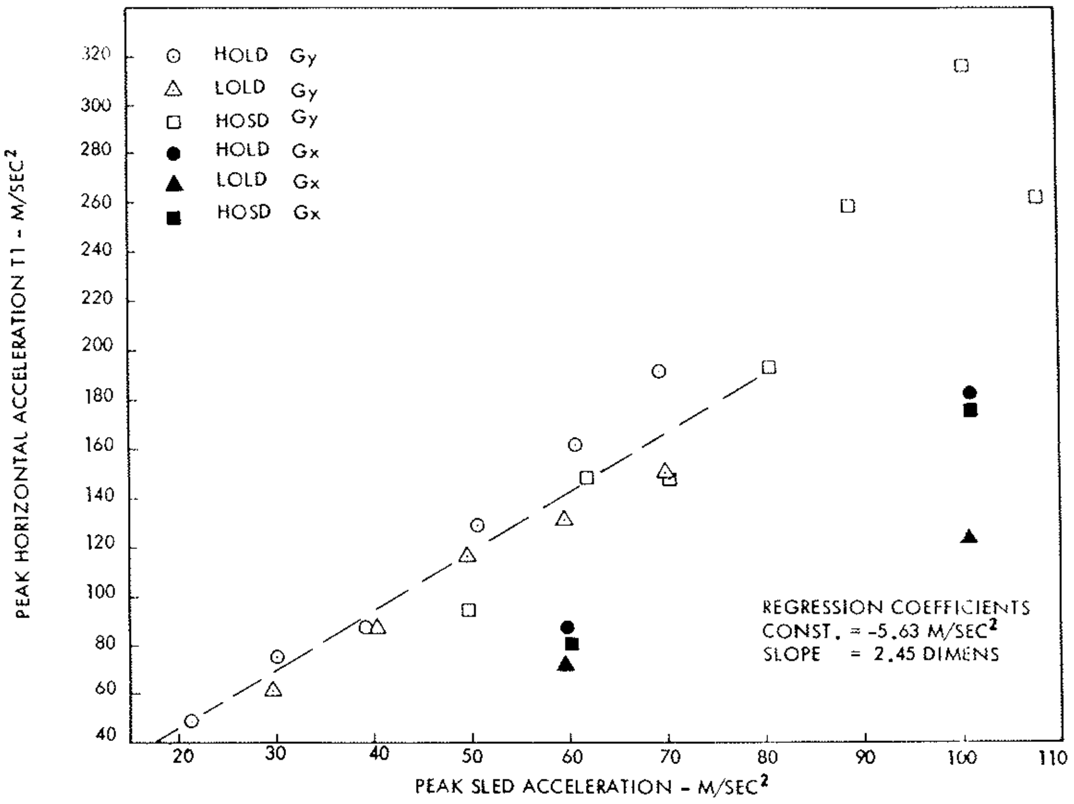


Fig. 10 - Peak horizontal acceleration at T_1 versus peak sled acceleration

Table IV - Regression on Sled Parameters

UNITS OF COEFFICIENTS CONSISTENT WITH

ANGLE - RADIANS
LENGTH - METERS
TIME - SEC.

INDEP. VAR. / DEPEND. VAR.	CONSTANT	PEAK SLED ACCEL.	SLED ONSET	SLED DUR.	STD. DEV.
ANG. ACCEL.	-526	19.1		2849	142.1
ANG. VEL.	-8.0542	.418	-.00035	67.9	2.67
RESULTANT LINEAR ACCEL.	-70.0	2.59	-.0053	468	17.9
HORIZ. ACCEL. AT T_1		2.48			38.4

If one compares these coefficients with those for the -Gx runs (11), there is good agreement in the coefficients for onset and duration but the coefficient on peak sled acceleration is approximately twice the value for +Gy as for -Gx. The explanation for this is found in the regression coefficient relating peak T1 linear acceleration to peak sled acceleration. This coefficient is twice the value for the +Gy runs compared to the -Gx runs.

For the -Gx acceleration vector the only significant component of angular acceleration and angular velocity is around an axis which is normal to the mid-sagittal plane. In contrast to this, analysis of the +Gy data indicates that although the head angular velocity was negligible around the anatomical Y axis (pitch), the component around the anatomical X and Z axes (roll and yaw respectively) were both significant. Therefore, the resultant angular acceleration and angular velocity around these two axes have been used in this +Gy study. The similarity in the shape of the components of angular velocity around the anatomical X and Z axes suggested that perhaps the direction of the angular velocity remained constant during most of the angular travel of the head.

Figure 11 is a plot of the direction of the angular velocity in the head anatomy superimposed on the resultant angular velocity. As can be seen from this figure, the angle that the angular velocity vector makes with the head anatomy is constant over the time where the angular velocity is appreciable. Although this figure is for a particular run in the study, it is indicative of most of the runs in the study independent of conditions or G level.

The angular velocity vector is in the mid-sagittal plane between the +X and -Z anatomical axes and makes an angle of approximately 0.6 radians with the +X axis. Table V shows the angle for five subjects at 5 and 7G for the HOLD condition. The angle is approximately constant across subjects and G levels and is consistent in both value and variability with a direction approximately normal to a neck line for the neck-up/chin-up (NUCU) initial condition (10).

These results together with observation of photographic data have reinforced the idea that for these +Gy runs the head rotates around a direction fixed in the laboratory and oriented approximately normal to the neck line defined between the T1 anatomical origin and the head anatomical origin.

Figures 1a through 1d show the orientation of the subject's head and neck during a +Gy acceleration run. The successive times selected are first motion of the sled, peak head angular

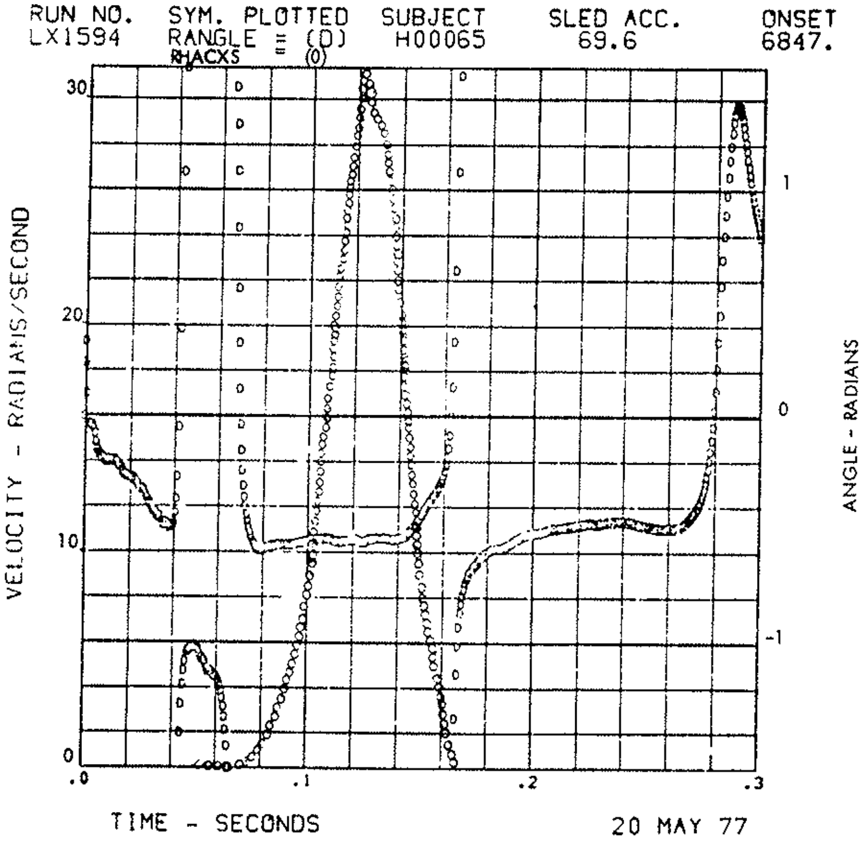


Fig. 11 - Resultant and direction of angular velocity vector (7G HOLD)

Table V - Direction of Angular Velocity Vector (HOLD Condition)

G level / Subject	5G		7G	
	Run Number	Rangle Radians	Run Number	Rangle Radians
H065	1581	.56	1594	.56
	1600	.58		
	1618	.62		
H075	1635	.60	1921	.58
	1827	.70		
H077	1633	.55	1922	.68
H078	1797	.48	1926	.46
	1824	.50		
H079	1798	.54	1924	.54
	1825	.60		

acceleration, peak head angular velocity and peak head angular displacement. The head appears to rotate as described around a direction fixed in the laboratory until near maximum angular deflection where the yawing component increases relative to the roll angular velocity.

The above result has far reaching implications regarding the degrees of freedom required in a head/neck model for the +Gy data base. A model with a hinge between the head and neck link oriented as described above and located to best fit the displacement data of the head relative to T_1 should be effective in representing the +Gy data base over much of the angular travel of the head. Future experiments are planned to determine the change in orientation of the hinge as a function of head and neck initial position for the +Gy acceleration vector.

CONCLUSIONS

1. The increased head angular acceleration in the +Gy runs relative to the -Gx runs is due to the increased peak acceleration at T_1 for the same sled acceleration. This increased T_1 linear acceleration is undoubtedly due to the different restraint employed with the +Gy runs.
2. With either +Gy or -Gx runs, the first peak value of T_1 horizontal acceleration determines the peak angular acceleration of the head.
3. Head angular acceleration can be predicted from the combined effects of peak sled acceleration and duration. However, this conclusion is strictly limited to the specific restraint and utilization of the restraint by the staff conducting the experiments.
4. The pattern of the time profiles for the output variables for +Gy runs is similar to that for the -Gx data base. However, the relative magnitude of the angular deceleration peak (second peak) to the acceleration peak (first peak) is greater for +Gy than for -Gx runs.
5. The head angular velocity for the long duration conditions (HOLD and LOLD) is not a significantly different function of the peak T_1 horizontal linear acceleration for the +Gy and -Gx data bases. The head angular velocity for the short duration condition (HOSD) is less for both +Gy and -Gx data bases. The major determinant on peak head angular velocity in both the +Gy and the -Gx studies is the peak T_1 horizontal acceleration with a secondary effect due to duration.
6. The head linear resultant acceleration is approximately

the same function of peak T_1 linear acceleration for conditions HOLD and LOLD in both +Gy and -Gx runs. The head linear acceleration is significantly less for the short duration condition (HOSD) with the effect of duration more pronounced in the +Gy than in the -Gx runs.

7. For the +Gy runs, the head rotates around an axis with a fixed orientation in the mid-sagittal plane approximately normal to the neck line defined as a line between the T_1 anatomical origin and the head anatomical origin. The variation of this axis orientation with subject initial condition will be developed in future experimental studies. Incorporating this constraint into a +Gy head/neck model should greatly simplify modeling efforts.

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