LIVING HUMAN DYNAMIC RESPONSE TO $-G_x$ IMPACT ACCELERATION

II. Accelerations Measured on the Head and Neck

Channing L. Ewing, Daniel J. Thomas, Lawrence M. Patrick

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U. S. ARMY AEROMEDICAL RESEARCH LABORATORY

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Abstract

A methodical investigation and measurement of human dynamic response to impact acceleration is being conducted as a Joint Army-Navy-Wayne State University investigation. Details of the experimental design were presented at the Twelfth Stapp Car Crash Conference in October 1968.

Linear accelerations are being measured on the top of the head, at the mouth, and at the base of the neck. Angular velocity is also being measured at the base of the neck and at the mouth. A redundant photographic system is being used for validation. All data are collected in computer compatible format and data processing is by digital computer. Selected data in a stage of interim analysis on 18 representative human runs of the 236 human runs completed to date are presented.

Review of the data indicates that peak accelerations measured at the mouth are higher than previous estimates. The time relationship of the peak resultant mouth accelerations to the peak sled acceleration for this particular accelerator and restraint system is described. The maximum peak resultant mouth acceleration was 47.8 g and the peak mouth angular velocity on another run exceeded 30 rad/sec, on nominal 10 g, 250 g/sec runs. Clinical evaluation of the subjects before and after the runs disclosed no evidence of unconsciousness or neurological deficit attributable to the acceleration.

Representative plots of the human dynamic response are presented, discussed, and compared. A first-order linear regression analysis for the peak mouth resultant acceleration and the peak mouth angular velocity obtainable from the peak sled acceleration is presented.

Note: This study is supported by U.S. Army Aeromedical Research Laboratory, Fort Rucker, Ala. Opinions or conclusions contained in this report are those of the authors and do not necessarily reflect the views or endorsement of the U.S. Army and U.S. Navy.

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A JOINT ARMY-NAVY-WAYNE STATE UNIVERSITY study of the dynamic response of the living human head and neck to $-G_x$ impact acceleration was announced at the Twelfth Stapp Conference (1).[2] While details of the experimental design, instrumentation, and photographic and data analysis systems can be found in the original presentation, a short summary is believed of value here.

Experimental Design—Dynamic response is defined as measured angular and linear accelerations on the head, and angular and linear displacements of the head from a reference point on the vertebral column where completely time-phased measurement of the input acceleration is made.

In the experiments, living human beings with subject-mounted instrumentation were seated on a steel chair rigidly mounted on a sled. Pelvic and torso restraint consisted of a wide lap belt with an inverted V strap and a standard aircraft shoulder harness. A chest safety strap also was used. Chair back height was adjusted for each subject.

The seated subjects were subjected to $-G_x$ impact acceleration, imposed by the Wayne State University WHAM II accelerator, at the acceleration end of the track. The end of the experimental conditions of interest occurred when dynamic response was substantially complete, and this occurred in every instance prior to the end of the initial acceleration pulse. The sled achieved a peak velocity which remained relatively constant until the sled brakes were activated. Sled braking produced a smooth 2 g deceleration until zero sled velocity was attained. Details of accelerator design were presented at the previous conference (2). Accelerator pulse shape for each run was triangular with a long decay.

Subject-mounted instrumentation included three anatomical mounting sites: over the posterior spinous process of the first thoracic vertebra (T_1), at the mouth, and over the posterior superior aspect of the head. Each anatomical mount was individually designed to prevent relative motion between the anatomical mounting site and the mount.

Each anatomical module was attached to a transducer module which consisted of an orthogonal pair of force-balance accelerometers with their sensitive axes in the midsagittal plane (plane of expected motion). In addition, the mouth and the T_1 transducer mounts each contained a subminiature rate gyroscope.

Photographic targets were rigidly mounted on the transducer mounts, and 16 mm pin-registered, high-speed, sled-mounted cameras were used for each run. Photographic data were time locked to tranducer data. Tracking of the head and spine systems both photographically and inertially allows crossvalidation of the data obtained.

Analog data were recorded on magnetic tape and then digitized at a sampling rate of 2000 samples/sec by an A/D converter and trans-

[2]Numbers in parentheses designate References at end of paper.

mitted to the core of the Univac 418 digital computer. Processing and analytical programs were then applied to the data.

Experimental Controls and Determinations—The following methods were used to determine the effects of different values of a single variable and to control the effects of other variables believed to influence the dynamic response:

1. To control the effect of rate of onset of acceleration, it was kept constant at 250 g/sec for the initial series of runs on each subject.

2. To determine the effect of rate of onset of acceleration the first step was to repeat the entire initial profile of increments of peak sled acceleration at a rate of onset double that of the initial series, that is, at 500 g/sec.

3. To control the effects of individual variation in muscle mass, strength, and other anthropometric and anthropomorphic sources of variance, each subject was used as his own control.

4. To determine the effects of subject size, subjects were selected on the basis of their sitting height, as determined by precise and extensive anthropometry (3).

5. To control the effect of variations in peak sled acceleration, the accelerator control settings were reproduced as nearly as possible for each run at a given peak-acceleration level.

6. To determine the effect of variations in peak sled acceleration, each subject was exposed to individual runs at 1 g increments from 3 through 10 g.

7. To control the effect of sled acceleration vector direction, it was kept constant for all runs.

8. To control the effect of variations in distance between accelerometers in the mount and that of spatial relationships between accelerometers and rate gyroscope, the accelerometers and rate gyroscope were locked into place on the transducer module, and the entire transducer module was shifted to the corresponding anatomical module of subsequent subjects. Thus the spatial relationships of the accelerometers and rate gyroscopes relative to each other for a given mount were constant for the entire series of runs.

9. To control the effect of differing distances between subjects from anatomical landmarks on any individual to the transducer module and photographic targets, precise photographic and X-ray anthropometry were performed on all subjects with the anatomical and transducer modules in place. For each individual, therefore, distances from external and internal landmarks to transducers and to the photographic targets were precisely known and did not vary from run to run on a given subject. Therefore, transformation of the measured accelerations and velocity from the point of measurement to the center of mass of the head of a given subject or to any specified location on the head of that subject is, theoretically, possible within a sagittal plane. These

transformations have not yet been performed but a workable technique is believed to be available.

10. To determine the effect of instrumentation weight and its distribution, each subject was exposed to several runs at both rates of onset with all mounts and photographic targets but with no instrumentation mounted except in the T_1 mount. These runs were termed unencumbered runs, and photographic data derived therefrom will be compared to those derived from fully instrumented runs. These data have not yet been analyzed.

11. To determine run-to-run repeatability for a given set of run parameters on individual subjects, multiple runs were performed on selected subjects at selected sled peak acceleration and rate of onset of acceleration values. These data have not yet been analyzed.

The effect of the restraint variable is assumed to be independant of the relationship between the T_1 acceleration and the head acceleration. However, as a practical matter each individual restraint system was adjusted as tightly as possible for each run, both as a safety measure and to keep the photographic targets within the field of view of the sled-mounted cameras. Parenthetically, it should be noted that the restraint adjustment procedure was determined experimentally to result in apparent excellent control of the restraint variable, as will be shown later. An analysis of the precise effects of variations in the restraint of an individual subject on the dynamic response of the head and neck must be performed, but has not yet been accomplished.

Run Profile—The control procedures developed for the experiment resulted in a complete experimental run profile for each subject, defined to include:

1. 3 g through 10 g at 250 g/sec in 1 g increments.
2. 3 g through 8 g at 500 g/sec in 1 g increments.
3. 6 g, 250 g/sec; 10 g, 250 g/sec; and 6 g, 500 g/sec unencumbered runs.

This involves a design goal of 17 runs for each subject.

Progress

To date there have been 236 human exposures to $-G_x$ impact acceleration. Of these, 30 early runs were incompletely instrumented and 7 were conducted on subjects wearing helmets; therefore, 199 human runs are available for data analysis.

Six subjects completed the defined experimental run profile for a total of 17 runs per subject. An additional two subjects completed runs through 6 g, 500 g/sec, omitting only the 7 and 8 g, 500 g/sec runs, for a total of 15 runs per subject. Of these eight subjects, two completed 9 g, 500 g/sec runs. Additional runs were made ranging in number from 1 through 11 by various other subjects.

All subjects were measured anthropometrically by Clauser (3). They ranged in sitting height from 34.8 to 38.5 in., corresponding to a range of 12th through 96th percentile according to the U.S. Navy Anthropometric Survey (4). Seven had sitting heights ranging from 85th through 96th percentile (37.5 through 38.5 in.) four from 47th through 60th percentile (36.2 through 36.6 in.), and five from 12th through 30th percentile (34.8 through 35.6 in.). These measurement data along with total body weight are presented in Table 1 for the subjects whose runs were selected for this interim report.

Selection of Data

Due to the extensive instrumentation, data retrieval, and data process-

Table 1—Selected Physical Anthropometric Data on Test Subjects

Subject No.	Sitting Height Inches[a]	Sitting Height Percentile[b]	Weight (lb)
010	38.5	96	176.5
007	38.5	96	154.5
003	36.4	53	157.5
016	36.2	47	166.5
009	35.1	17	155.6
013	34.8	12	133.7

[a]From Clauser (3).
[b]From NAEC-ACEL Report 533 (4).

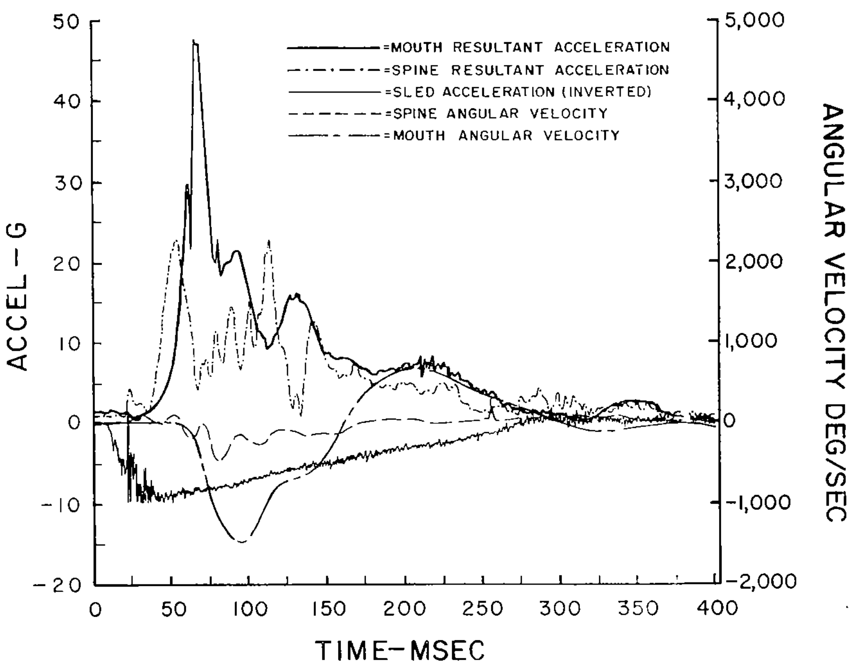

Fig. 1—Plot of resultant acceleration and angular velocity measured at T_1 and at the mouth of a 12th percentile subject for nominal 10 g, 250 g/sec run

ing arrangements outlined in the previous report, large masses of data have become available. It was necessary in view of time constraints to select for the present interim report data which were available in an intermediate stage of analysis on representative subjects. Therefore, exposures at 3, 6, and 10 peak sled g, with rate of onset 250 g/sec only, on two subjects in each of three groups of approximately the 15th, 50th, and 96th percentile in sitting height, were selected for comparison. The selection was *not* at random, but was made on the basis of subject size and data availability.

Experimental Results

Measured sled acceleration is the line inverted for clarity in the computer plot presented as Fig. 1. Note that duration of sled acceleration pulse is about 275 ms for the nominal 10 g sled peak with rate of onset of acceleration of 250 g/sec.

Resultant accelerations measured at T_1 and at the mouth are presented, as well as angular velocity measured at T_1 and at the mouth. With the subject facing to the right, and viewed from his right side, angular velocities clockwise are negative in sign and those counterclockwise are positive.

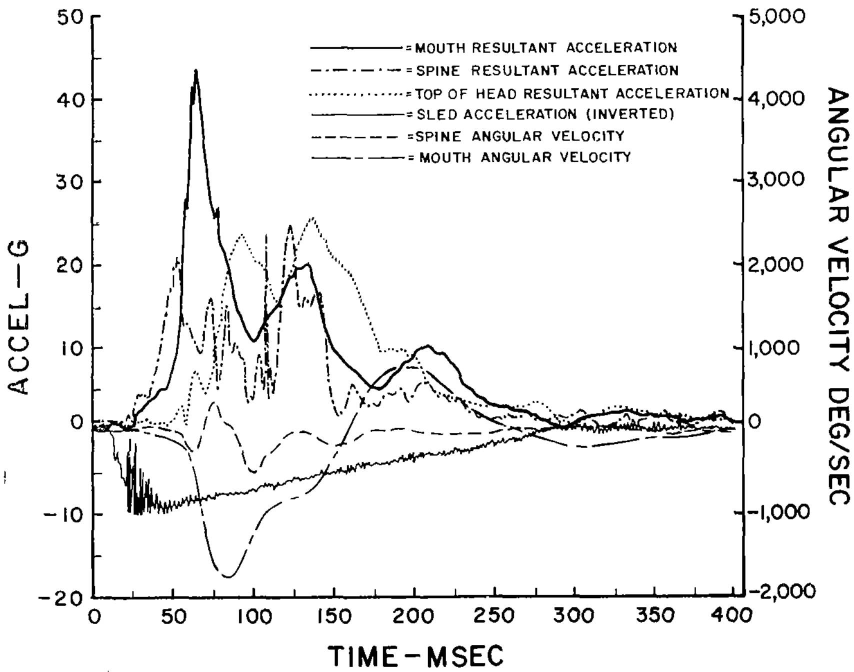

Fig. 2—Plot of resultant acceleration at mouth, head, and T_1, and angular velocity at mouth and T_1 on a 96th percentile subject for nominal 10 g, 250 g/sec run

Peak resultant mouth acceleration for nominal 10 g sled peak is seen to be 48 g, and peak angular velocity at the mouth 1500 deg/sec. This value was the highest mouth resultant peak acceleration measured on any of the runs in this entire series.

Fig. 2 shows the same data as those presented in Fig. 1 on a nominally identical run conducted on a 96th percentile subject (sitting height). Measured peak mouth angular velocity on the living human subject is seen to be 1784 deg/sec or 31.14 rad/sec. Peak angular acceleration has not yet been calculated. Mahone, et al. have stated that, in man, 30 rad/sec angular velocity and 1800 rad/sec^2 angular acceleration are needed to produce concussion (5). The latter criteria were developed by photographic data analysis from monkeys subjected to whiplash accelerations with the data scaled to a brain of the approximate weight of that of man, given as 1300 gm in his calculations.

Clinical data from the human subject taken both before and after the run, shown in Fig. 2 revealed only a history of headache occurring under the head anatomical mount, with no history of actual stunning, loss of consciousness, or functional impairment. Telemetered EEG data of good quality are available but have not yet been interpreted. It is anticipated that all physiological data from these runs, including respiratory rate, EKG, and EEG, will be made the subject of a separate paper to be published subsequently.

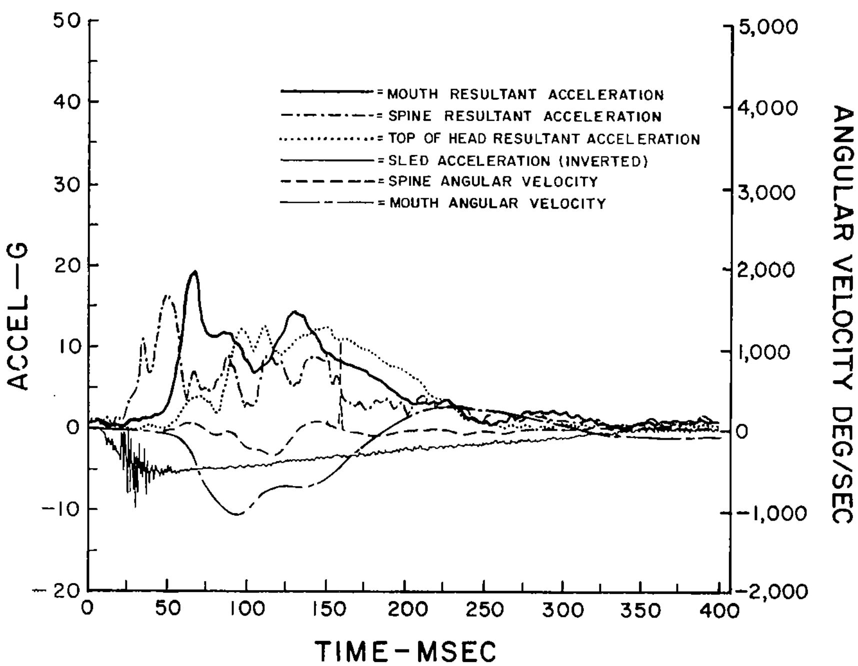

Fig. 3—Plot of resultant acceleration at mouth, head, and T_1 and angular velocity at mouth and T_1 on a 12th percentile subject for a nominal 6 g, 250 g/sec run

Fig. 3 shows for the same subject as Fig. 1, a plot of the same parameters for a nominal 6 g, 250 g/sec run. Peak mouth acceleration resultant is 19 g, and peak mouth angular velocity is 1050 deg/sec. The relationship between peak mouth resultant acceleration and peak sled acceleration for 3 g, 6 g, and 16 g, 250 g/sec runs reported herein is presented in Fig. 4.

Fig. 5 demonstrates that the mouth resultant acceleration curves for all six subjects show similarities on the 3 g, 250 g/sec runs. Peak accelerations ranged 4.5-7 g. Time synchronization of acceleration curves is noticeable in several instances.

Fig. 5 also demonstrates that on one subject (010) there is no definite peak mouth resultant acceleration. It is presumed that this may be due to variations in voluntary contraction of neck muscles.

Fig. 6 is a plot of mouth resultant accelerations for all six individuals subjected to nominal 10 g, 250 g/sec runs. Peak values range, however, from 32 g through 48 g. These curves show greater similarity than do those in Fig. 5.

In order that the curves presented be understood, it is necessary to explain the means by which the computer automatically establishes experimental zero time or Data Processing Time Zero (DPTZ). All data presented are referenced to this initial point in time. Sled acceleration is averaged and the peak is determined from the averaged data. The point at

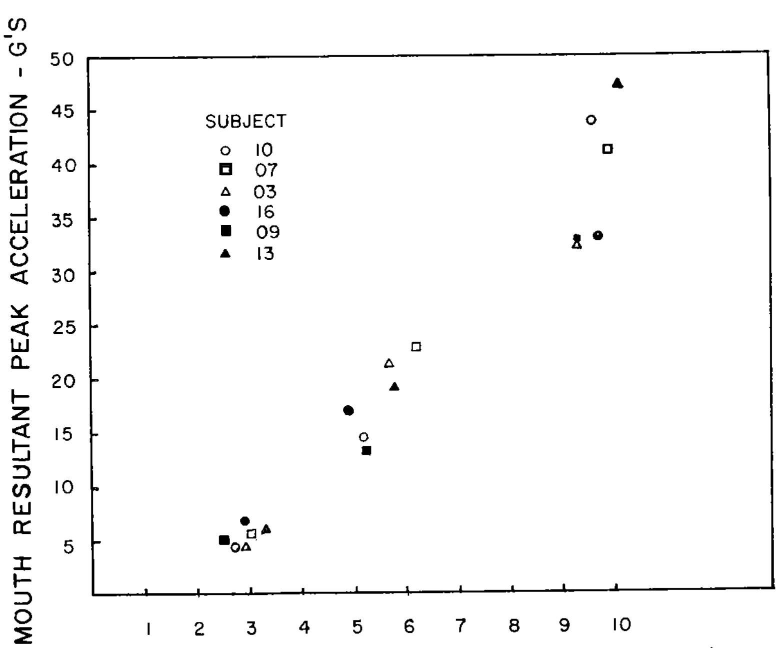

FIG. 4—Measured sled peak acceleration versus mouth resultant peak acceleration

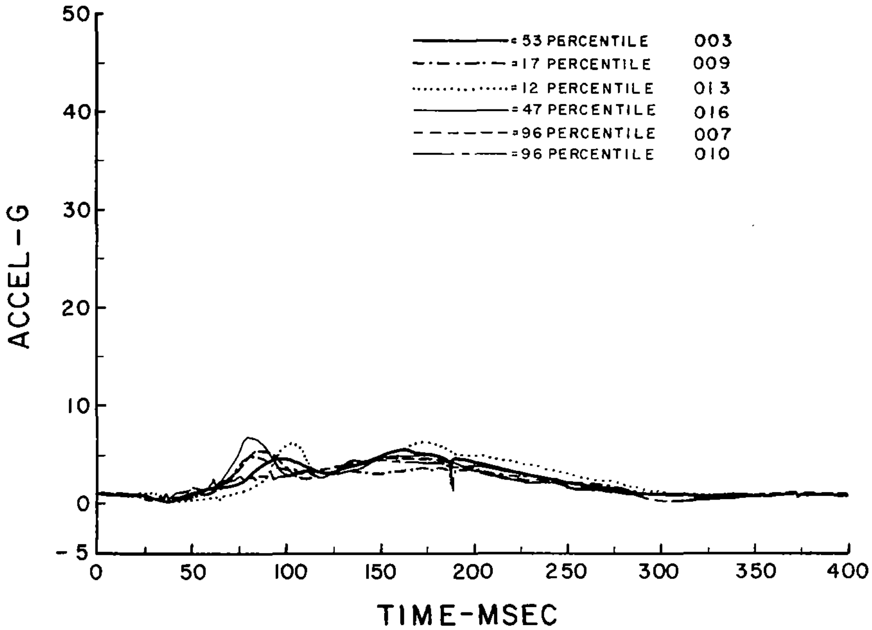

FIG. 5—Plot of mouth resultant acceleration for nominal 3 g, 250 g/sec run on the six selected subjects for this report

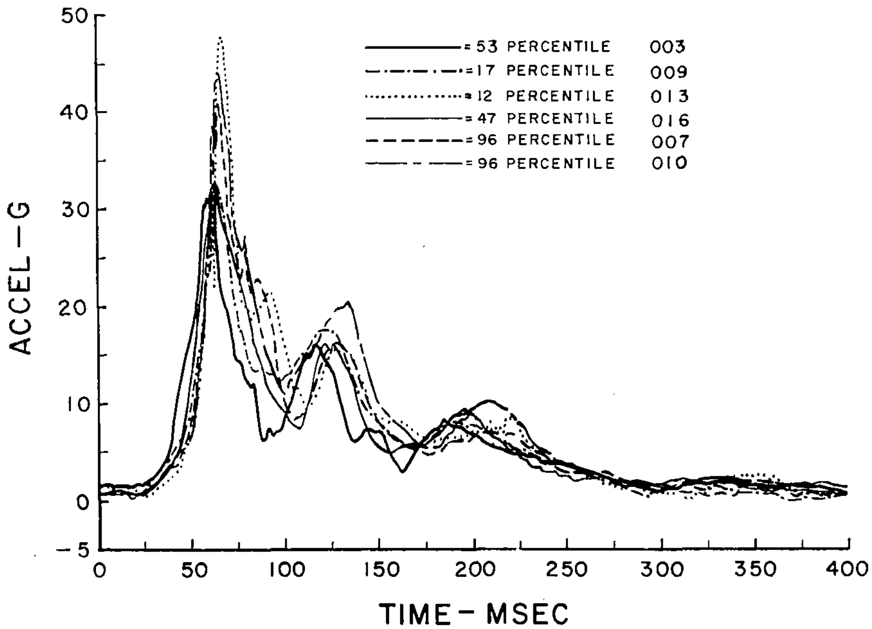

Fig. 6—Plot of mouth resultant accelerations for nominal 10 g, 250 g/sec runs on the six selected subjects

which 40% of the peak amplitude was reached is then determined and DPTZ is established by counting back for a fixed time (15 ms).

Synchronization of the time from DPTZ to peak mouth resultant acceleration from subject to subject for nominally identical runs probably is a function of the reproducibility of the following factors:

1. The sled acceleration pulse shape.
2. Determination of DPTZ.
3. Subject restraint.
4. The characteristics of human head and neck dynamic response.

Other factors may conceivably cause variations in the time from DPTZ, but the stated causes of variance are believed to be the major ones.

On the six 10 g, 250 g/sec runs reported here, however, the *mean* time from DPTZ to peak mouth resultant acceleration was 63.5 ms, with a standard deviation of 1.64 ms. Examination of the peaks in Fig. 6 shows the marked coincidence from subject to subject of these peak acceleration curves.

In attempting to rule out all the major possible sources of variance even this small, the averaged sled peak accelerations for each run plotted in Fig. 6 were plotted in Fig. 7. While one pulse is slightly displaced in time, it is felt that the coincidence of sled pulses in Fig. 7 is remarkable, and indicates that the total variance introduced both by computer determination of DPTZ and that induced by lack of production of similar sled pulse shapes from run of run is very small. The major sources of any variance, therefore, could only be variation in subject restraint from subject to

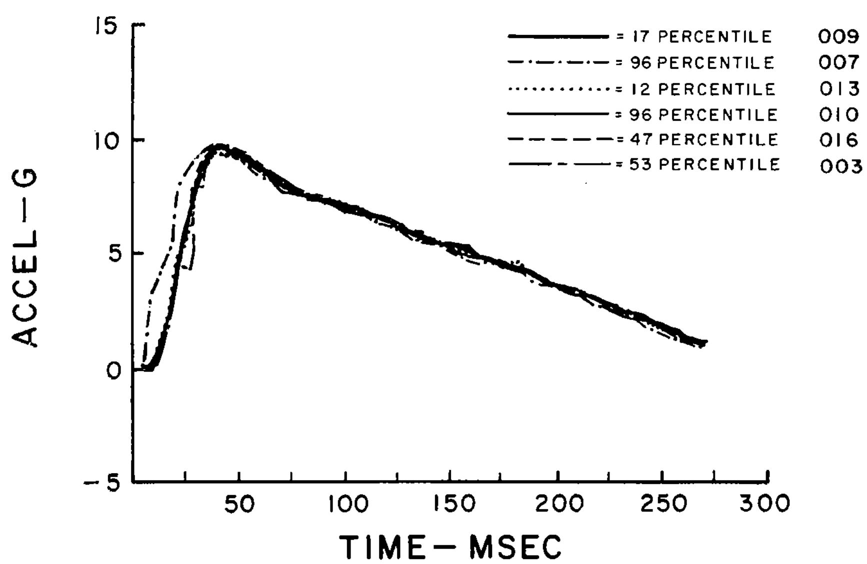

FIG. 7—Plot of the averaged sled acceleration for the nominal 10 g, 250 g/sec runs on the six selected subjects

subject, and variation due to human dynamic response from subject to subject.

Due to the small total variance, it is believed that, as stated earlier, subject restraint from one subject to another within this series was quite constant. Therefore, one must consider that there are marked and important similarities in the time phasing of the dynamic response of the human head and neck to experimentally induced impact accelerations.

It may be noted that Fig. 6 presents data only out to 400 ms after DPTZ. When the original runs were undertaken, the duration of dynamic response of the head and neck to the input acceleration pulse was unknown. Examination of the data for all runs reveals that significant dynamic response is complete well within 250 ms after DPTZ regardless of nominal sled peak acceleration. The resultant acceleration amplitudes at the three anatomical mounting sites become essentially identical to sled acceleration within the 250 ms period, as can be determined by examining Figs. 1, 2, and 6. This statement can be made only with respect to the characteristic WHAM II accelerator pulse shape, however.

Table 2 presents nominal and measured peak values for the selected runs. Sled acceleration is the scaled reading of a single accelerometer, not a resultant.

In the experimental design, one of the fundamental assumptions was that the head acts as a rigid body. Therefore, measured accelerations at the head and mouth are meaningful only if relative motion between the head and mouth mounts is determined to be small. While complete data are not yet available for all runs considered here, examination of photo-

Table 2—Selected Data Points from 18 Runs Involving 6 Subjects

Subject No.	Nominal Peak Sled G	Measured Peak Sled G[a]	Mouth Resultant Peak G[b]	Mouth Peak Angular Velocity deg/sec[b]
010	3	2.7	4.5	300
007	3	3.0	5.6	400
003	3	2.9	4.6	450
016	3	2.9	7.0	390
009	3	2.5	5.0	300
013	3	3.3	6.1	500
010	6	5.2	14.5	900
007	6	6.2	22.9	1000
003	6	5.7	21.5	1075
016	6	4.9	17.0	800
009	6	5.2	13.2	825
013	6	5.8	19.2	1050
010	10	9.6	44.0	1780
007	10	9.9	41.3	1675
003	10	9.3	32.6	1310
016	10	9.7	33.2	1350
009	10	9.3	32.7	1160
013	10	10.1	47.8	1490

[a]As determined from analog strip chart readouts.

[b]As determined from plots of scaled digitized acceleration resultants and angular velocity.

graphic data on four of the 6 g runs indicates that maximum change in distance between mouth and head photographic targets averaged 6 mm during the period of maximum acceleration, with the actual values being 4, 6, and 8 mm. This distance change is only about 2% and is considered to be insignificant. The limit of photographic resolution is only 2.5 mm.

The scatter diagram of Fig. 8 demonstrates the clustering of peak values of mouth angular velocity for the stated sled peak accelerations, from which the linear regression analysis was derived.

For the selected runs, the regression analysis of the relationships of the peak mouth resultant accelerations and peak mouth angular velocities to the peak sled acceleration is summarized in Table 3, based on the data presented in Table 2.

The analysis demonstrates that in the selected runs, under the experimental conditions previously noted, the peak mouth resultant acceleration and peak mouth angular velocity can be predicted with a high degree of confidence from run to run, and from subject to subject, on the basis of nominal of measured peak sled accelerations of the WHAM II accelerator. Similar analysis or the relation of mouth acceleration measurements to spine acceleration measurements based on peak readings alone was not carried out because of the complex waveform of the spine measurements, and must await a more complete waveform analysis of the spine accelerations.

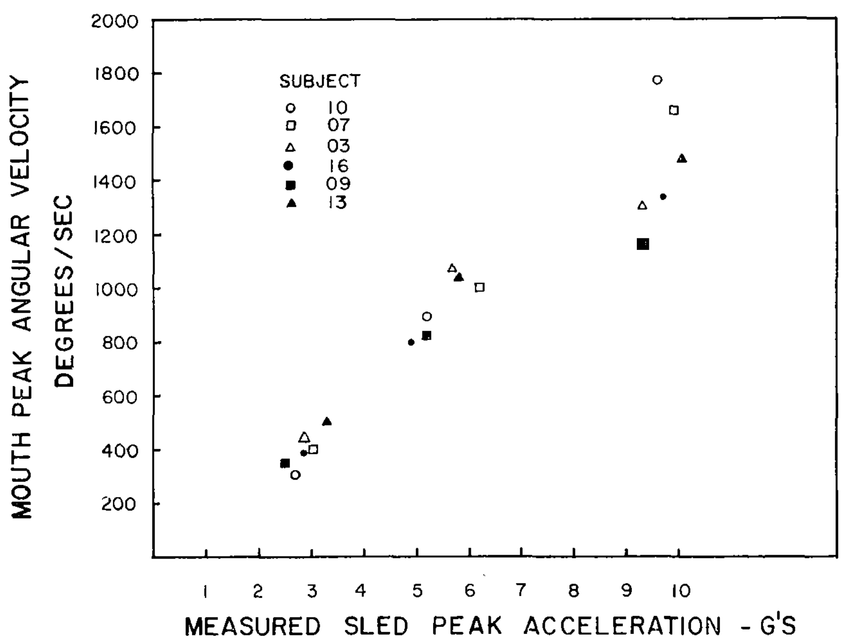

Fig. 8—Measured sled peak acceleration versus mouth peak angular velocity

Table 3—Statistical Summary of Data Presented in Table 2

Variable		Correlation Coefficient (r)			First Order Regression Coefficient ($b_{y \cdot x}$)			
Y	X	Estimate	95% Confid. Interval	Regression Constant ($a_{y \cdot x}$)	Estimate	95% Confid. Interval	$^t b > o$	Standard Error ($S.E._{y \cdot x}$)
Mouth resultant peak acceleration, g	Nominal sled peak acceleration, g	0.95	0.87-0.98	— 9.92	4.88	4.05-5.71	12.51[a]	4.77
Mouth resultant peak acceleration, g	Measured sled peak acceleration, g	0.97	0.92-0.99	— 9.54	5.09	4.43-5.74	16.33[a]	3.71
Mouth peak angular velocity, deg/sec	Nominal sled peak acceleration, g	0.94	0.84-0.98	—30.14	151.74	123.69-179.79	11.44[a]	161.37
Mouth peak angular velocity, deg/sec	Measured sled peak acceleration, g	0.96	0.89-0.98	—11.56	156.79	131.25-182.31	13.25[a]	144.12

[a] $p < 0.001$.

The correlation coefficients relating both the mouth resultant peak accelerations and mouth peak angular velocities to the sitting heights of the six subjects for the selected runs did not demonstrate a significant relationship at the $p = 0.05$ level. A correlation coefficient of 0.811 would be required to establish significance at the $p = 0.05$ level with an n of only six subjects for any given run. The inclusion of data from additional subjects would make it possible to demonstrate a significant relationship with a lesser correlation coefficient value, if any relationship does indeed exist.

Conclusion

From the results of the 18 selected human runs the following conclusions can be drawn:

1. The mouth resultant acceleration plots of different living human subjects exposed to very similar sled acceleration peaks show important similarities in shape and phase relationship, thus raising the hope that descriptive equations can be written to generalize these findings to the general population.
2. The similarities increase with increasing sled peak acceleration.
3. No relationship was established between peak mouth resultant acceleration or peak mouth angular velocity and subject sitting height.
4. Variations in peak mouth resultant accelerations and peak mouth angular velocities as a result or restraint variation is minimal, as implied by the correlation of these parameters to peak sled acceleration.
5. First order linear regression analysis shows the amplification relationship of mouth resultant acceleration and peak mouth angular velocity to the peak sled acceleration.
6. Clinical examination of a subject on whom the peak mouth angular velocity exceeded 30 rad/sec, before and after this individual run, showed no changes attributable to the acceleration event. Exhaustive analysis of the physiological data will be subsequently presented when available.
7. In the course of 236 human impact acceleration exposures involving 17 subjects, no injuries occurred other than minor, superficial contusions due to the restraint system.

Summary

The current state of the Joint Army-Navy-Wayne State University experimental approach to the determination of the dynamic response of the human head and neck to impact acceleration has been presented. The interim experimental results available on 18 selected runs involving 6 subjects have been presented. Two hundred thirty-six (236) human runs have been completed with no injury other than superficial abrasions due to restraint.

Initial analysis of relationships of peak amplitudes of the inertial data has been completed on the 18 selected runs. The peak mouth resultant acceleration shows an amplification factor of four or more over the peak sled acceleration. The peak mouth angular velocity was 30 rad/sec without clinically observable effects due to the acceleration, on a subject during a 10 g run. The similarities of amplitude and phase relationships of the dynamic response of the six subjects at a selected sled acceleration level are striking. No significant relationship between peak mouth resultant acceleration or peak mouth angular velocity and the sitting height of the six selected subjects was demonstrated.

Acknowledgments

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13. ABSTRACT A methodical investigation and measurement of human dynamic response to impact acceleration was conducted as a Joint Army-Navy-Wayne State University investigation. Details of the experimental design were presented at the Twelfth Stapp Car Crash Conference in October 1968.

Linear accelerations were measured on the top of the head, at the mouth, and at the base of the neck. Angular velocity was also measured at the base of the neck and at the mouth. A redundant photographic system was used for validation. All data were collected in computer-compatible format and data processing was by digital computer. Selected data in a stage of interim analysis on 18 representative human runs of the 236 human runs completed to date are presented.

Review of the data indicates that peak accelerations measured at the mouth are higher than previous estimates. The time relationship of the peak resultant mouth accelerations to the peak sled acceleration for this particular accelerator and restraint system is described. The maximum peak resultant mouth acceleration was 47.8 g and the peak mouth angular velocity on another run exceed 30 rad/sec, on nominal 10 g, 250 g/sec runs with no evidence of unconsciousness or neurological deficit attributable to the acceleration.

Representative plots of the human dynamic response are presented, discussed, and compared. A first-order linear regression analysis for the peak mouth resultant acceleration and the peak mouth angular velocity obtainable from the peak sled acceleration is presented. Important similarities discovered in the time phasing of the human dynamic response to impact accelerations are presented and discussed.

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Impact acceleration						
Acceleration tolerance						

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