6-2001

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HUMAN HEAD-NECK KINEMATIC RESPONSE TO IMPACT ACCELERATION: COMPARISON OF OBLIQUE TO COMBINED FRONTAL AND LATERAL RESPONSE

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ESV Paper Number 196

ABSTRACT

This paper relates human oblique head-neck kinematics to human frontal and lateral head-neck kinematics for three subjects of varying anthropometry. Head-neck kinematic response to indirect impact acceleration for an oblique test is compared to the superposition of the head/neck behavior of appropriate frontal and lateral tests for the same subject. The results have important implications in terms of the complexity required in the design and validation of omni-directional biofidelic crash test manikins and mathematical models of human head-neck response.

INTRODUCTION

The National Crash Survival Databank (NCSDB) at the National Biodynamics Laboratory (NBDL) in New Orleans, is the repository of indirect impact acceleration test data from approximately 2700 tests involving over 200 human research volunteers (HRV's) conducted during the last 30 years. These data describe the dynamic response of the head and neck to various sled acceleration profiles and head/neck initial conditions. While the frontal (-X) and lateral (+Y) test results have been extensively reported [1-4], the results of the oblique -X+Y tests, for various reasons, have never been formally presented.

The purpose of this paper is to express oblique head-neck kinematics as a combination of frontal and lateral head-neck kinematics. While [5] presents an omni-directional head/neck mechanical linkage model useful for high g-level tests in the -X+Y, -X, and +Y impact directions, we present a simplified qualitatively accurate "additive" analysis of head/neck kinematics, useful at lower g-levels. No assumptions regarding underlying geometric and mechanical properties of the head/neck system are made.

Head and neck kinematic data from seventy-six horizontal sled tests involving seven human research volunteers of varying anthropometry have been analyzed. These tests were selected from three test series conducted at NBDL during 1981 and 1982.

Motion of the head and neck with respect to the sled and the neck acceleration components driving the motion of the head are considered. The head-neck kinematics for an oblique test are compared with the combination of the kinematics for appropriately chosen frontal and lateral ("component") tests for the same subject. This analysis has important implications for the design and validation of omni-directional biofidelic crash test manikins (e.g. THOR) and mathematical models of frontal, lateral, and oblique human head-neck response, especially for low-speed impacts.

EXPERIMENTAL DESIGN

The head and neck kinematic data for this paper were collected in three test series: Series 40, a -X (frontal) series, Series 42, a +Y (lateral) series, and Series 43, a -X+Y (oblique) series conducted at NBDL in 1981 and 1982. Data for seven HRVs, H-130 through H-136, were used in this analysis but, due to space constraints, we present results for three subjects only: H131, H132, and H134. Basic physical anthropometry parameters for these three volunteers are shown in Table 1.

Table 1.
General Anthropometric Data

H ID	Age (yrs)	Stature (cm)	Weight (Kg)	Sitting Ht (cm)
131	20	167.0	67.6	90.0
132	21	172.9	79.8	89.6
134	20	178.3	75.3	93.0

Table 2 defines the sled acceleration profile parameters and Table 3 lists the head and neck linear and angular kinematic variables. Detailed definitions of the sled acceleration profile parameters, the head and neck kinematic variables, and all pertinent coordinate systems (C.S.) used (laboratory, sled, head anatomical, and T-1 (neck) anatomical) are described in [1,3]. Initial conditions for kinematic variables are denoted with a final subscript of 0 while resultants are denoted by R in place of X, Y or Z (e.g., $N@Xv_0$ for initial neck angular velocity and HRd for resultant head linear displacement).

This paper presents data sets for 3 volunteers subjected to peak sled accelerations of 6g's in the -X and +Y directions and 9g's in the -X+Y (45°) oblique direction. All tests examined were run in the neck up, chin up head/neck initial position.

Table 2.
Sled Parameters

Name	Unit	Definition
PSA	m/s^2	Peak sled acceleration
ESV	m/s	Endstroke sled velocity (ΔV)
ROO	m/s^3	Rate of onset
DOP	ms	Dwell time above 75% PSA

Table 3.
Head/Neck Kinematic Variables

Type	Name	Definition	C.S.
Linear Acc. (m/s^2)	HXa, NXa	X-component	Sled
	HYa, NYa	Y-component	
	HZa, NZa	Z-component	
Angular Acc. (rad/s^2)	H@Xa, N@Xa	About X-axis	Head, Neck Anat.
	H@Ya, N@Ya	About Y-axis	
	H@Za, N@Za	About Z-axis	
Linear Vel. (m/s)	HXv, NXv	X-component	Sled
	HYv, NYv	Y-component	
	HZv, NZv	Z-component	
Angular Vel. (rad/s)	H@Xv, N@Xv	About X-axis	Head, Neck Anat.
	H@Yv, N@Yv	About Y-axis	
	H@Zv, N@Zv	About Z-axis	
Linear Disp. (m)	HXd, NXd	X-component	Sled
	HYd, NYd	Y-component	
	HZd, NZd	Z-component	
Angular Disp. (rad)	H@Xd, N@Xd	About X-axis	Head, Neck Anat.
	H@Yd, N@Yd	About Y-axis	
	H@Zd, N@Zd	About Z-axis	
Linear Acc. (m/s^2)	NaXH,	X-component	Head Anat.
	NaYH	Y-component	
	NaZH	Z-component	

RESULTS

The sled acceleration vector with respect to the gross anatomy of the seated volunteer for a -X+Y (45°) oblique test may be decomposed into a -X (frontal) component and a +Y (lateral) component, nominally perpendicular to one another and of equal magnitude. Hence, a 9g -X+Y oblique test is thus approximately comparable to the combination of a 6g -X test and a 6g +Y test ($\sqrt{(6^2 + 6^2)} = 8.5$).

The head angular motion for a -X (frontal) test is almost totally about the head anatomical Y axis. The head angular motion for a +Y (lateral) test appears like a roll around an axis in the mid-sagittal plane of the head, with positive angular velocity component about the head anatomical X axis and a negative angular velocity component about the head anatomical Z axis. Practically no angular velocity component is present about the head anatomical Y axis (pitch). The acceleration and velocity components for a -X+Y (45°) oblique test have angular components about the anatomical X and Z axes similar to those observed in a +Y test and an angular component around the anatomical Y axis similar to a -X test. To this extent, volunteer head motion in an oblique test can be represented as the combination of the head motions in appropriately-chosen -X and +Y "component" tests.

The main driver for the head angular motion for a +Y test is the component of neck (T-1) linear acceleration along the instantaneous head anatomical Y axis (NaYH). The drivers for the head angular motion for a -X test are the components of the neck (T-1) linear acceleration along the instantaneous head anatomical X and Z axes (NaXH, NaZH).

The motion of the head/neck is dependent upon many factors, including the acceleration inputs to the neck and the head, the initial orientation of the head/neck system, and the geometric configuration and mechanical properties of the various components of the cervical spine and the head.

The sled parameter and head/neck initial orientation data for the 6g -X and +Y and the 9g -X+Y tests for subjects H-131, 132 and 134 are given in the following tables and the resulting head/neck kinematics are displayed in the accompanying figures. The first two rows of plots compare the 9g -X+Y head angular accelerations and velocities with those obtained from the appropriate 6g -X or +Y test "component" test and those obtained from the sum of the two "component" tests. The third row of plots compares the driving accelerations for the head angular motion (i.e., the components of the neck (T-1) linear acceleration along the instantaneous head anatomical X, Y, and Z axes) for the 9g -X+Y test and the appropriate 6g "component" test.

Figure 1 and Table 4 summarize the results for subject H-131. There is quite good agreement of the H@X and H@Z accelerations for the -X+Y test, the +Y 'component" test and the sum of the +Y and -X "component" tests up to maximum angular velocity. Also, the corresponding driving neck acceleration curves (third row, middle plot), show excellent agreement . The -X+Y H@Xa and H@Za curves are narrower and fall and rise more sharply than their +Y counterparts. This is partially due to the higher g-level (4 %) and the higher rate of onset (almost double) of the sled acceleration profile for this test vis á vis its +Y "component" test. With regard to angular velocity, the peak magnitudes of H@Xv and H@Zv for the -X+Y test are significantly smaller than those for its +Y "component" test. This indicates less angular travel in -X+Y tests than in their "component" -X and +Y tests. There is a large disparity in the H@Ya curves for the -X+Y test and the corresponding -X "component" test. This discrepancy is correlated with the disparity in the neck acceleration components driving H@Ya, namely, the components of the neck (T-1) linear acceleration parallel to the X and Z axes of the (moving) Head Anatomical Coordinate System (HACS). We denote these accelerations by NaXH and NaZH. The H@Yv curves have different shapes but approximately equal first peak magnitudes.

Table 5 and Figure 2 summarize the results for subject H-132. There is excellent shape agreement up to maximum angular velocity for the H@Xa, H@Ya, and H@Za curves. First peak magnitude agreement for H@Ya and H@Za is excellent, while H@Xa first peak magnitude is significantly smaller for the -X+Y test. The peak magnitudes of the H@Yv and H@Zv curves compare well but the -X+Y test angular velocity curves are narrower, dropping off much faster subsequent to peak angular velocity. The level of agreement of the curves for the driving neck linear acceleration component, NaYH, correlates well with the level of agreement of the driven angular accelerations H@Xa and H@Za. However, while H@Ya curve agreement is excellent, there is much less agreement of the driving neck accelerations NaXH and (especially) NaZH.

Table 6 and Figure 3 summarize the results for subject H-134. Shape and peak magnitude agreement for H@Xa, H@Ya, and H@Za is excellent up to peak angular velocity and, in the case of H@Xa, well beyond peak angular velocity. Again, the -X+Y test angular velocity curves are narrower, dropping off much faster subsequent to peak angular velocity. The level of agreement of H@Xa and H@Za curves correlate reasonably well with the level of agreement of the NaYH driving acceleration. However, the H@Ya curve agreement is excellent in spite of a total lack of agreement in the driving neck accelerations, NaXH, and NaZH.

Figure 4 summarizes the head angular displacement results for all three subjects. For all subjects the best agreement occurs for H@Yd both in peak magnitude and shape. H@Zd agrees reasonably well in shape but is much shallower. H@Xd is significantly different in shape roughly approximating the negative of the dominant component and sum behavior for H-131and H-134 and correctly directed but much shallower for H-132. In all cases the peaks for the 9g -X+Y test occurs much earlier than its dominant 6g component or the sum.

Figure 5 summarize the head linear displacement results for all three subjects. For all subjects the best agreement occurs for HXd both in peak magnitude and overall shape. HZd agrees reasonably well in shape but is much shallower. HYd is significantly different in shape roughly approximating the shape of the negative of the dominant component and sum behavior for H-131and H-132 and correctly directed but much shallower for H-134. In all cases the peaks for the 9g -X+Y test occurs much earlier than its dominant 6g component or the sum and the curve is more sharply peaked and more quickly decreasing after peak displacement. Nevertheless, the resultant linear displacements agree reasonably well in shape and peak magnitude.

CONCLUSIONS

1. The head angular acceleration and velocity curves for a -X+Y sled acceleration profile can be synthesized with reasonable accuracy from -X and +Y "component" tests. The sled profiles for these "component" tests are obtained by resolving the -X+Y sled profile into roughly equal components along the -X and +Y direction of the initial head anatomical axes.

2. The synthesized -X+Y curves always agree with the actual -X+Y curves in direction and are reasonably correct in (first) peak amplitude.

3. The shape agreement of the actual and synthesized -X+Y curves is best up to peak angular velocity and degrades quickly with increasing angular travel.

4. Shape agreement in the head curves does not correlate with shape agreement in the driving neck accelerations.

5. The H@Ya and H@Yv curves for a -X+Y test are more peaked at maximum angular velocity and are flatter on the pre- and post-peak portions of the sled acceleration profile than their -X component test counterparts.

6. The degradation of shape and peak magnitude agreement at significant angular travel indicates that the rotational compliances about the head axes are interdependent for large rotations.

7. Linear displacements degrade far less in magnitude and shape agreement.

FURTHER WORK

The authors are currently extending the "additive" analysis presented here to other head/neck initial positions and sled acceleration profiles. Since the shape and direction of the synthesized curves are similar to the true -X+Y curves, we would like to investigate synthesizing the -X+Y response by adding appropriately scaled -X and +Y components.

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ACKNOWLEDGEMENTS

We kindly acknowledge NBDL personnel who were involved in the acquisition and preliminary analysis of human -X+Y head/neck response, including Dr. Ewing, Dr. Thomas, Mr. Lustick, Mr. Willems, and Mr. Bartholomew.

This work was performed in part under ONR Grant No. N00014-98-1-0335. The opinions and interpretations contained herein are those of the authors and do not necessarily represent the views, policies, or endorsements of the Department of the Navy or any other Government agency.

Table 4.
Test Conditions for Subject H-131

Dir	G's	HXd_0 (m)	HYd_0 (m)	HZd_0 (m)	$H@Xd_0$ (rad)	$H@Yd_0$ (rad)	$H@Zd_0$ (rad)	NXd_0 (m)	NYd_0 (m)	NZd_0 (m)	$N@Xd_0$ (rad)	$N@Yd_0$ (rad)	$N@Zd_0$ (rad)	PSA m/s^2	ESV m/s	ROO m/s^3	DOP ms
-X	6.1	-1.31	-0.03	1.56	0.038	-0.07	0.005	-1.32	0.01	1.40	0.06	-0.14	-0.011	59.3	9.84	1321	120
+Y	6.2	-1.38	0.04	1.56	0.067	-0.06	1.686	-1.37	0.03	1.41	0.05	0.07	1.626	60.6	7.22	1301	89
-X+Y	9.2	-1.33	0.03	1.57	0.078	-0.07	0.776	-1.35	0.03	1.40	0.00	0.04	0.903	89.4	12.9	2334	107

Figure 1. Subject H-131: Comparison of 9g -X+Y test with the sum of a 6g -X and a 6g +Y test.

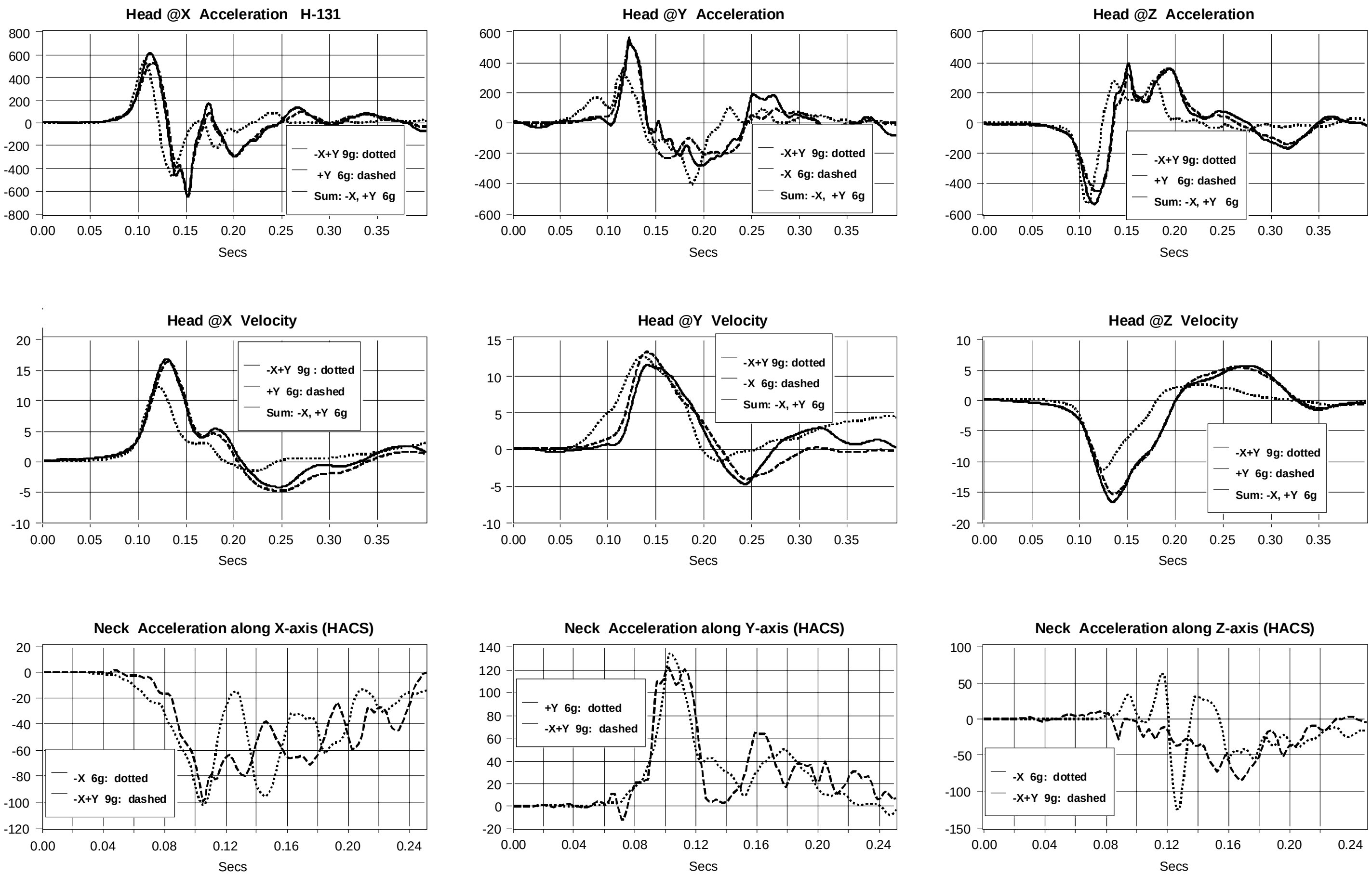


Table 5.
Test Conditions for Subject H-132

Dir	G's	HXd_0 (m)	HYd_0 (m)	HZd_0 (m)	$H@Xd_0$ (rad)	$H@Yd_0$ (rad)	$H@Zd_0$ (rad)	NXd_0 (m)	NYd_0 (m)	NZd_0 (m)	$N@Xd_0$ (rad)	$N@Yd_0$ (rad)	$N@Zd_0$ (rad)	PSA m/s^2	ESV m/s	ROO m/s^3	DOP ms
-X	6.3	-1.31	0.02	1.53	0.002	-0.29	-0.090	-1.31	0.01	1.39	-0.04	0.222	0.140	61.0	9.96	1371	119
+Y	6.1	-1.41	0.06	1.53	0.142	-0.04	1.425	-1.41	0.04	1.39	-0.37	-0.028	1.800	59.6	7.14	1272	91
-X+Y	9.0	-1.34	0.07	1.53	0.085	-0.08	0.700	-1.36	0.04	1.40	-0.25	0.194	0.996	87.9	12.7	2349	106

Figure 2. Subject H-132: Comparison of 9g -X+Y test with the sum of a 6g -X and a 6g +Y test.

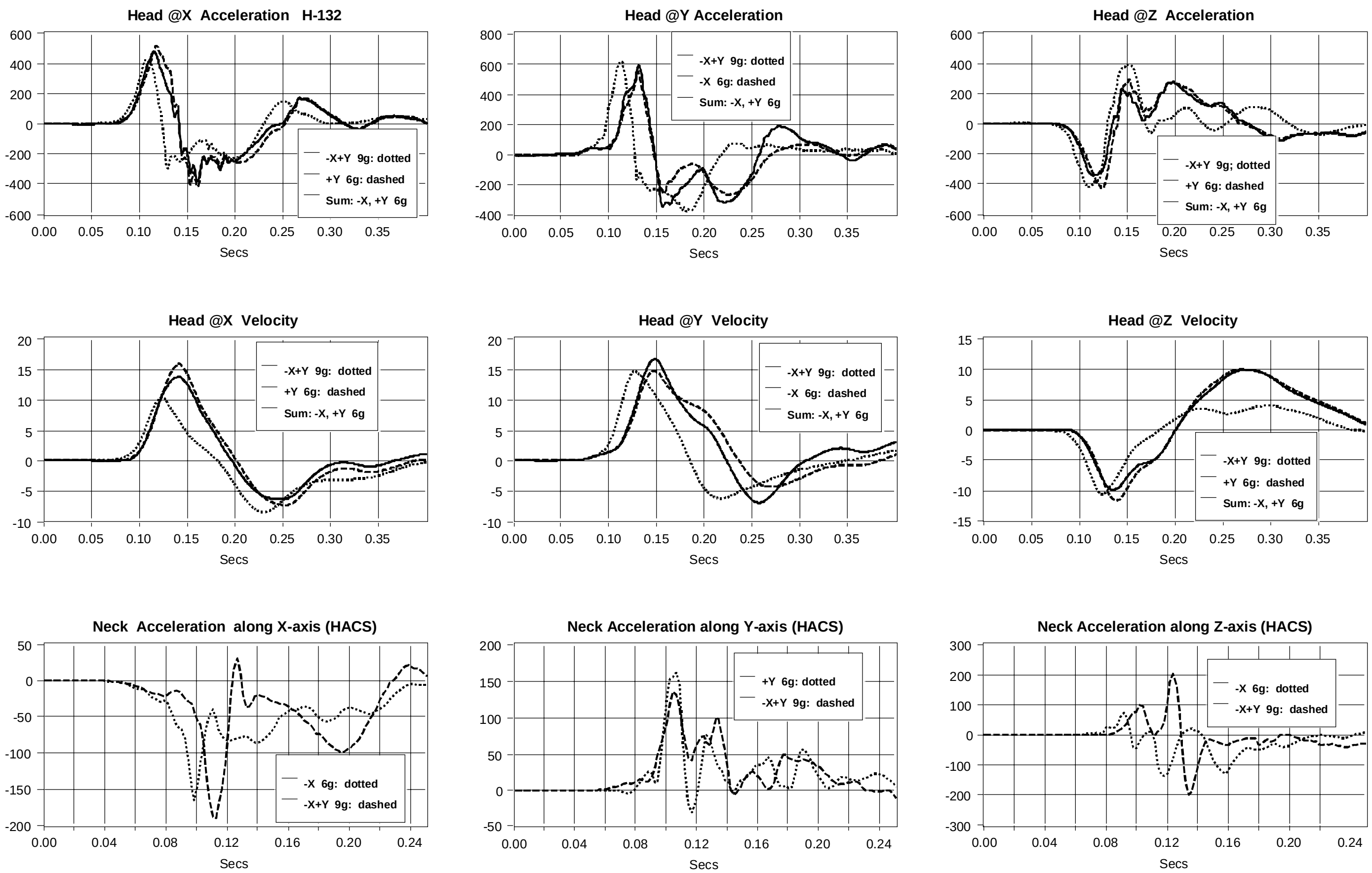
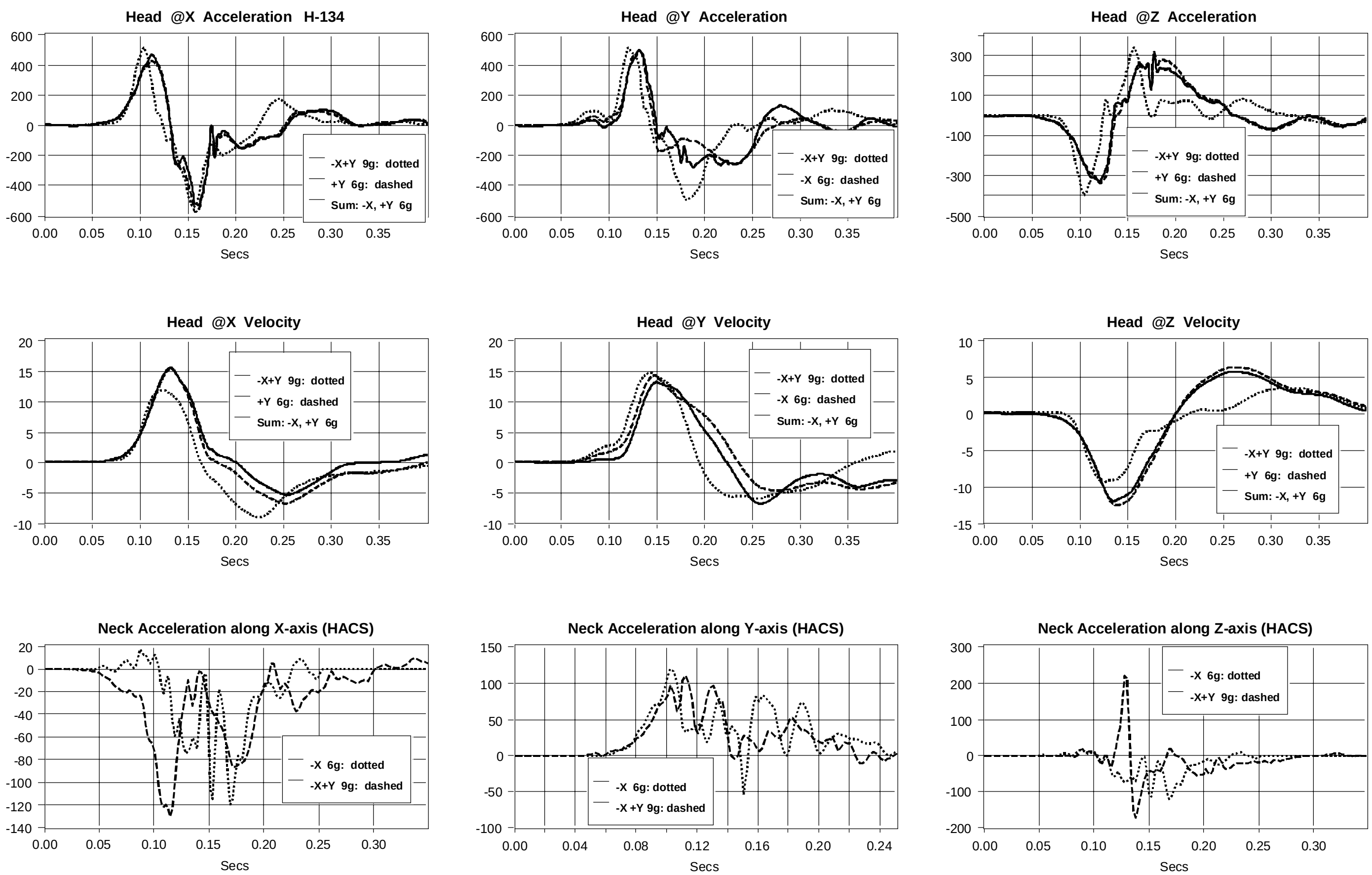


Table 6.
Test Conditions for Subject H-134

Dir	G's	HXd_0 (m)	HYd_0 (m)	HZd_0 (m)	$H@Xd_0$ (rad)	$H@Yd_0$ (rad)	$H@Zd_0$ (rad)	NXd_0 (m)	NYd_0 (m)	NZd_0 (m)	$N@Xd_0$ (rad)	$N@Yd_0$ (rad)	$N@Zd_0$ (rad)	PSA m/s^2	ESV m/s	ROO m/s^3	DOP ms
-X	6.3	-1.33	-0.001	1.56	0.015	-0.100	-0.021	-1.34	0.001	1.38	-0.07	0.228	0.177	60.9	9.96	1356	119
+Y	6.1	-1.37	0.003	1.58	0.155	-0.100	1.678	-1.38	0.010	1.41	-0.33	-0.055	1.607	59.9	7.13	1257	89
-X+Y	9.3	-1.36	0.015	1.57	0.152	-0.107	0.834	-1.35	0.019	1.41	-0.24	0.155	0.896	89.5	12.9	2388	107

Figure 3. **Subject H-134: Comparison of 9g -X+Y test with the sum of a 6g -X and a 6g +Y test**.



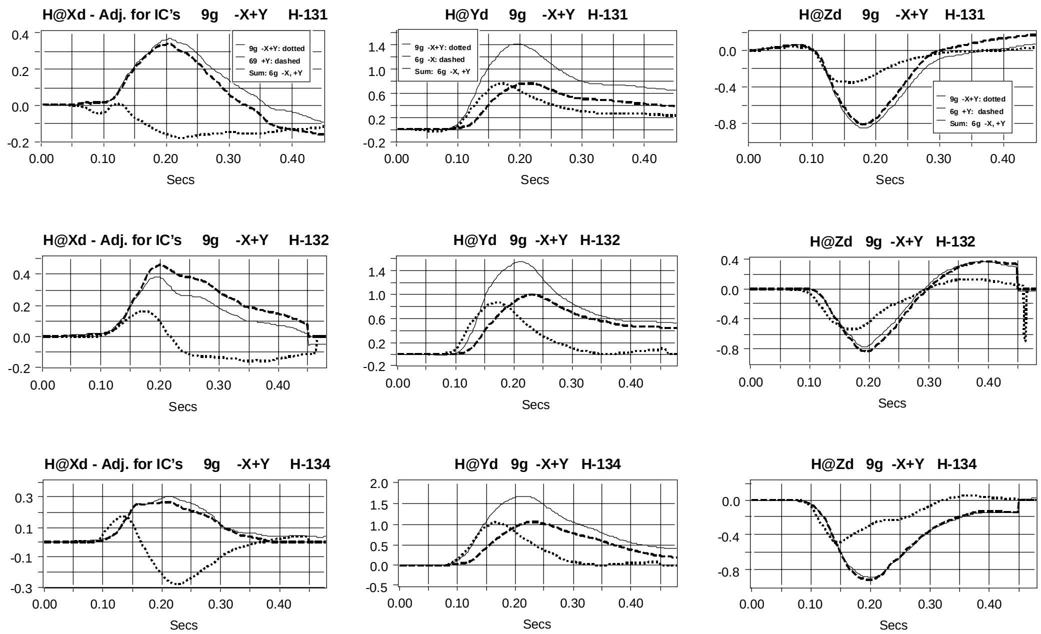


Figure 4. **Comparison of angular displacements for 9g -X+Y tests with the sum of a 6g -X and a 6g +Y tests for three subjects**.

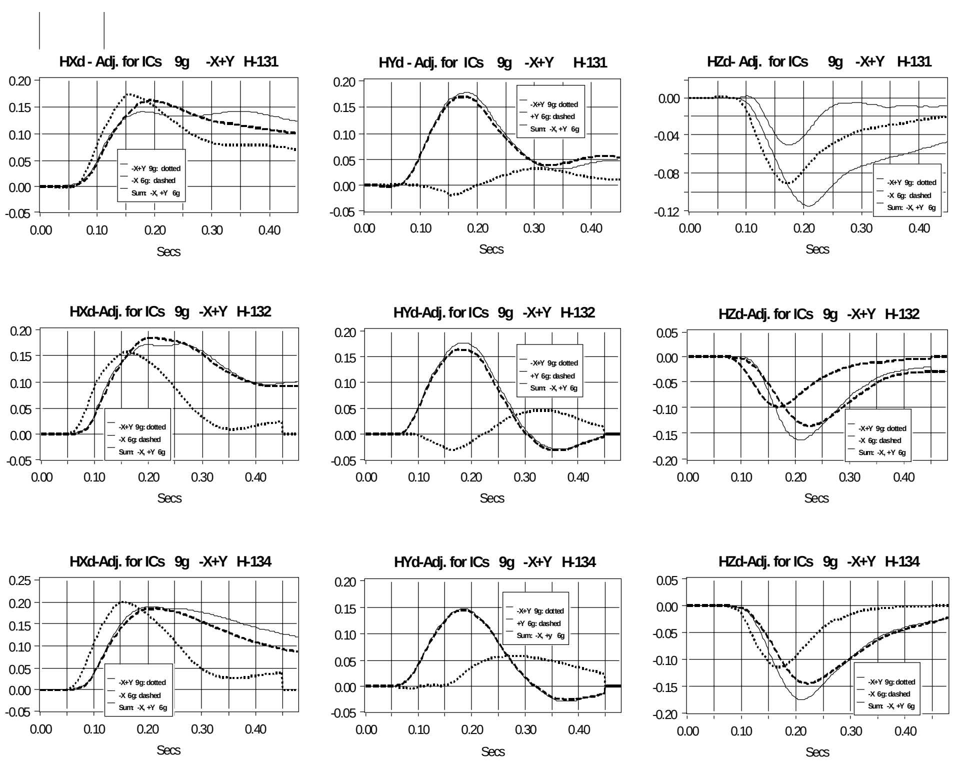


Figure 5. **Comparison of linear displacements for 9g -X+Y tests with the sum of a 6g -X and a 6g +Y tests for three subjects**.