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A Consistent Statistical Model for Human Kinematic Response to Impact Acceleration

Terry A. Watkins
Mathematics Department, University of New Orleans
S. J. Guccione, Jr.
Mathematics Division, Naval Biodynamics Laboratory

Abstract: A consistent statistical model for human head kinematic response was developed for a set of fifty-seven -Gx human impact acceleration experiments conducted at the Naval Biodynamics Laboratory (NAVBIODYNLAB). The acceleration levels ranged from 6 to 15 g's. The six responses modelled were the X and Z components of head linear acceleration with respect to the sled, the angular acceleration about the Y-axis of the head anatomical coordinate system [1,2] and the associated linear and angular displacements. Appropriately windowed acceleration curves were fitted to parameterized polynomial-type splines using non-linear least squares techniques. The spline parameters were in turn predicted from certain sled acceleration and initial head orientation parameters [3,4,5] to obtain predicted mean acceleration responses. Doubly integrated fitted acceleration responses, adjusted for initial conditions, provided the corresponding fitted displacement responses.

Introduction: Human and rhesus head kinematic data can both be used to develop human head injury prediction models for impact acceleration environments. While human head-neck kinematics for the -X vector direction have been successfully modelled utilizing a deterministic head-neck linkage model [1,6-10] driven by accelerations at T-1, the first thoracic vertebral body, the lack of rhesus T-1 data precludes the development of a similar animal model. The large database of rhesus kinematic, injury and pre-injury data [11,12] collected at the Naval Biodynamics Laboratory requires other means for scaling human and rhesus head kinematic responses. Although no deterministic linkage model is available for rhesus head-neck kinematics, there is convincing visual evidence that the underlying structure of key human and rhesus responses is essentially the same [13]. Since the same sled and initial head orientation parameters are available for human and rhesus impact acceleration tests, efforts have been made to predict key human and rhesus head responses from these common inputs. The results in [13] show that the key peaks of human -Gx mid-sagittal kinematic responses regress excellently on sled and initial head orientation parameters. Those in [14] show that human and rhesus head acceleration and displacement response traces can individually be fitted to common parametric models. However, the parameters in these models are not easily interpreted and the acceleration models cannot be simply integrated to obtain the corresponding displacement models. Therefore, integrable models for the various head accelerations employing simple functions of the key peak magnitudes and timings as parameters were developed. This paper presents the results of this third phase of study, namely, the consistent statistical modelling of key human -Gx head kinematic response curves.

Methodology: The first step in the curve fitting procedure was the windowing of the head acceleration traces. The time window for each acceleration curve was chosen narrow enough to eliminate early startup behavior and late-occurring voluntary response yet wide enough to provide fitting the corresponding displacement trace beyond its sole primary peak. The resulting acceleration curve was modelled as A=A(t;P) where the form of A is known and P is a vector of fitting parameters closely related to peak magnitudes and timings. For each acceleration curve for each test, nonlinear least squares was used to estimate P. This provided a fitted acceleration curve $A=F(t;\hat{P})$ where $\hat{P}$ is the estimate of P. $\hat{P}$ was then predicted from an input vector X containing sled acceleration and initial head orientation parameters. This provided a predicted mean acceleration response $A=F(t;\hat{\hat{P}}(X))$ where $\hat{\hat{P}}(X)$ is the estimate of $\hat{P}$ based on X.

To obtain fitted displacement responses, the fitted acceleration curve $A=F(t;\hat{P})$ was doubly integrated and then adjusted for initial conditions using the observed displacement data[1]. The resulting adjusted displacement curve $D=D(t;\hat{P},\hat{a})$, where $\hat{a}$ is the least squares estimate of the adjustment vector, provided the appropriate fitted displacement response. Appendices A and B and plots 3-14 in appendix C explain the modeling procedure in more detail.

Results: As figures 15, 17, 19 in Appendix C indicate, the linear and angular acceleration responses were generally well predicted by the vector X of sled and head initial orientation data. The R^2 values associated with the times to peak and peak values generally ranged from .75 to .95. Since the second segment of each acceleration curve is determined by these parameters, this segment is highly predictable. The R^2 values for the parameters associated with the first segment of the acceleration curves are generally much smaller. The only exception is the X-component of linear acceleration (AAX). Hence, the initial portion of the various acceleration curves is generally less predictable. The adjusted fitted displacements (figures 16, 18, 20, Appendix C) provided excellent fits to the observed displacements.

Conclusions: The results obtained in this study support the feasibility of employing statistical predictive models for human head kinematic response to -Gx impact acceleration. The simplicity of functional form and physical significance of the parameters in these models is especially appealing. Another crucial feature of this approach is the ability to predict key kinematic responses without the use of any anthropometric variables. Thus, this approach is very robust across the range of head/neck anthropometry present in human research volunteers.

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[1]This adjustment was necessitated by: (1) Inherent inconsistencies between sensor-derived acceleration data and photo-derived displacement data; and (2) Inconsistencies introduced by the selective windowing of acceleration and displacement responses.

Future work: Modified models yielding much improved prediction for the initial segment of the acceleration responses have already been developed. The regression equations for the fitted displacement responses and confidence bands for all the predicted mean responses are being determined. Additional human -Gx kinematic data will be used to validate the predictive power of the refined models.

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Disclaimer.

The interpretations and opinions in this work are the author's and do not necessarily reflect the policy and views of the Navy or other government agencies.

Human Use Statement.

Volunteer subjects were recruited, evaluated, and employed in accordance with the procedures specified in the Department of Defense Directive 3216.2 and Secretary of the Navy Instruction 3900.39 series. These instructions meet or exceed prevailing national and international standards for the protection of human subjects.

Animal Use Statement.

The animals used in this work were handled in accordance with the principles outlined in the guide for the care and use of laboratory animals (National Institutes of Health Document No. NI4 80-23) established by the Institute of Laboratory Animal Resources, National Research Council, Bethesda, MD.

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Appendix A. Definitions of Sled Acceleration, Head Initial Orientation and Head Kinematic Response Variables.

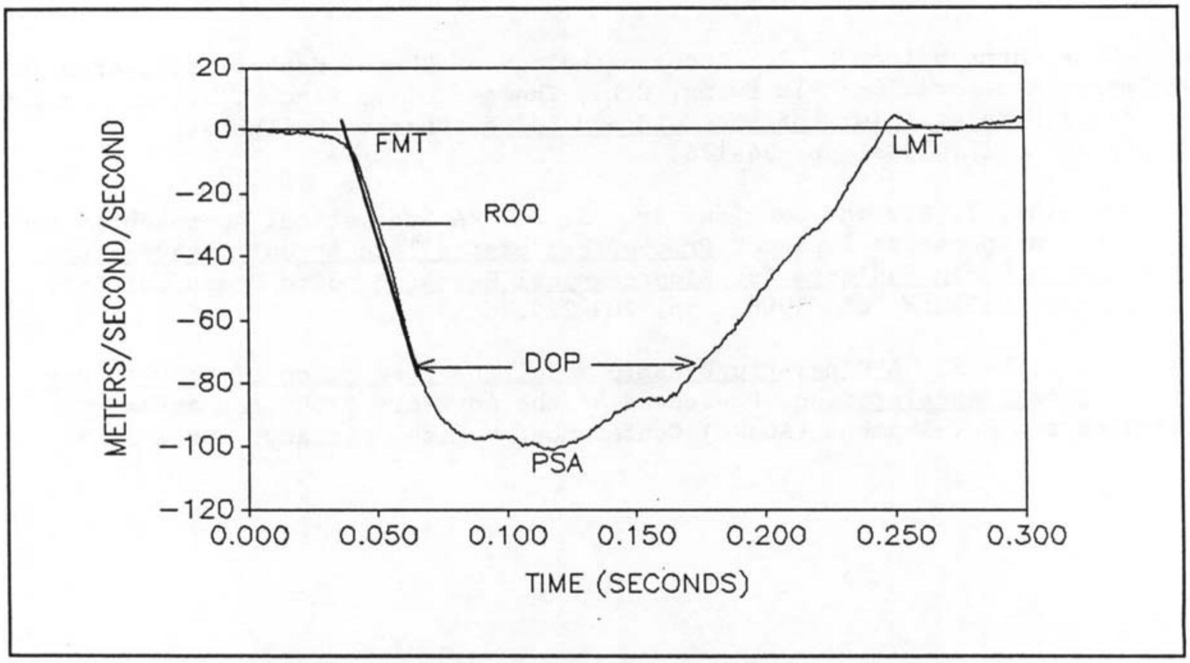


Figure 1. Sled acceleration profile for 10g -X human run.

Table A.1: Definition of Sled Parameters

PSA	Peak Sled Acceleration Unsmoothed peak of the sled acceleration profile	m/sec^2
ESV	Endstroke Sled Velocity Velocity acquired between time of first motion (FMT) and end of sled acceleration (LMT)	m/sec
ROO	Rate of Onset Slope of least squares line fit to the portion of the sled acceleration profile in the range [0.2 PSA, 0.5 PSA] and before the time of PSA	m/sec^3 or g/sec
DOP	Duration of Peak The total amount of time spent above 75% of PSA	msec

Table A.2: Definition of Initial Head Orientation Variables

Name	Description	Units	Coordinate System
DAX_0	The initial X-component of linear displacement	meters	Sled
PHB_0	The initial angle of rotation about the Y-axis (pitch)	radians	Head anatomical
DAZ_0	The initial Z-component of linear displacement	meters	Sled

Input Parameter Vector:

$$X = [\ PSA,\ ESV,\ ROO,\ DOP,\ PHB_0,\ DAX_0,\ DAZ_0]$$

Table A.3: Definition of Head Kinematic Response Variables

Name	Description	Units	Coordinate system
QHB	Angular acceleration about Y-axis	rad/sec^2	Head anatomical
PHB	Y-component of head angular displacement	radians	Head anatomical
AAX	Linear acceleration along X-axis	m/sec^2	Sled
DAX	X-component of head linear displacement	meters	Sled
AAZ	Linear acceleration along Z-axis	m/sec^2	Sled
DAZ	Z-component of head linear displacement	meters	Sled

Appendix B. Example of Statistical Modeling Procedure

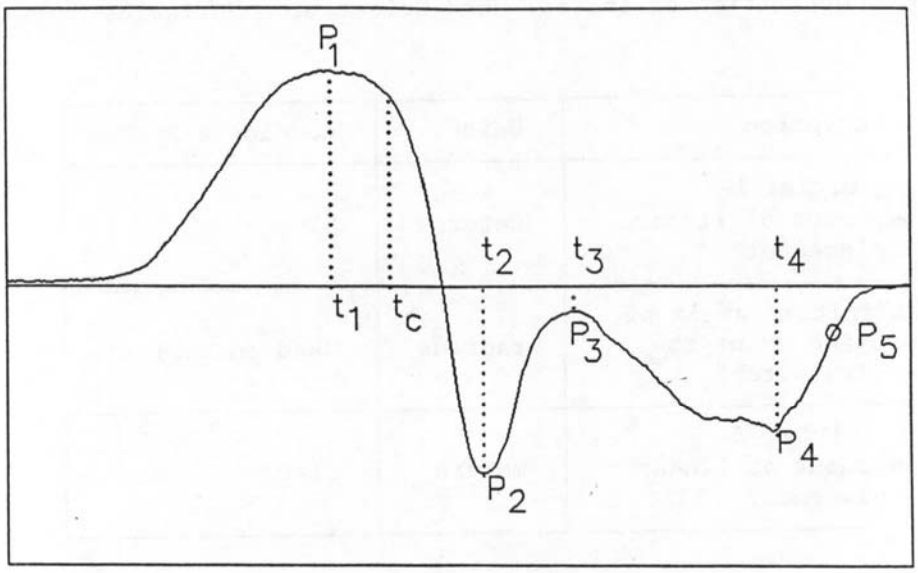


Figure 2. Key peaks and times for modeling the X-component of head linear acceleration in the sled coordinate system (AAX).

MODEL FOR X-COMPONENT OF HEAD LINEAR ACCELERATION (AAX)

$$A'(t) = \begin{cases} C_0(t-t_1)t^{b-1}, t \le t_c \\ (t-t_2)(t-t_3)(t-t_4)\sum_{k=0}^{4} a_k t^k, t \ge t_c \end{cases}$$

Require A and A′ to be continuous at $t = t_c$.

Model Parameters:

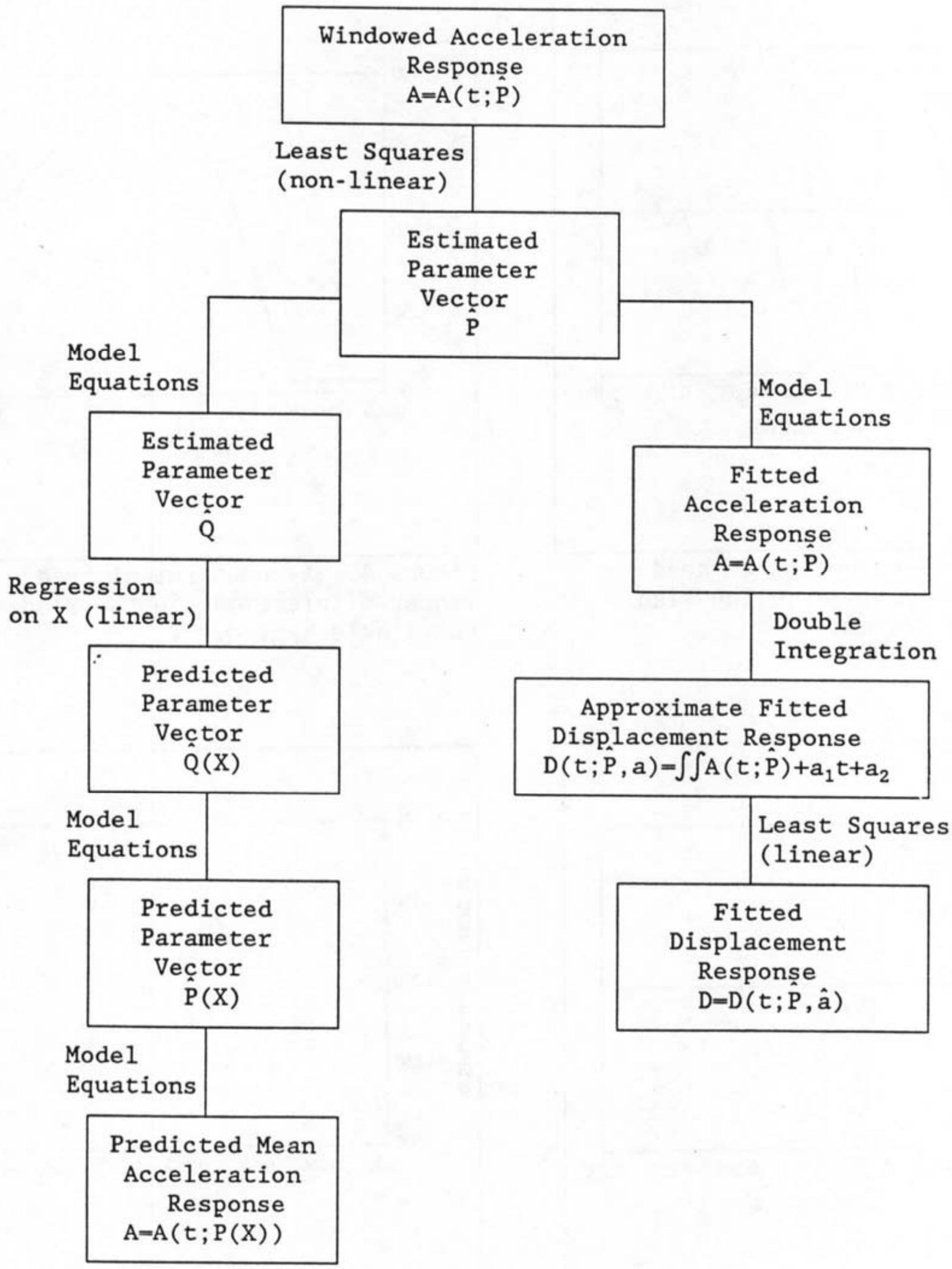
- b = shape parameter
- C_0 = shape parameter
- t_c = connect time for the two pieces of the spline
- p_1-p_4 = key peaks
- t_1-t_4 = times to peak
- p_5 = magnitude at t_4 +10 msec
- a_0-a_4 = functions of peaks and times to peak

Model Parameter Vectors: (10 parameter model)

$$P = \left[b, t_c, t_1\text{-}t_4, a_1\text{-}a_4 \right]$$

$$Q = \left[t_c, t_1\text{-}t_4, p_1\text{-}p_5 \right]$$

PARAMETER ESTIMATION, CURVE FITTING AND REGRESSION TECHNIQUES



Appendix C. Plots of Observed, Windowed, Fitted and Predicted Head Kinematic Responses

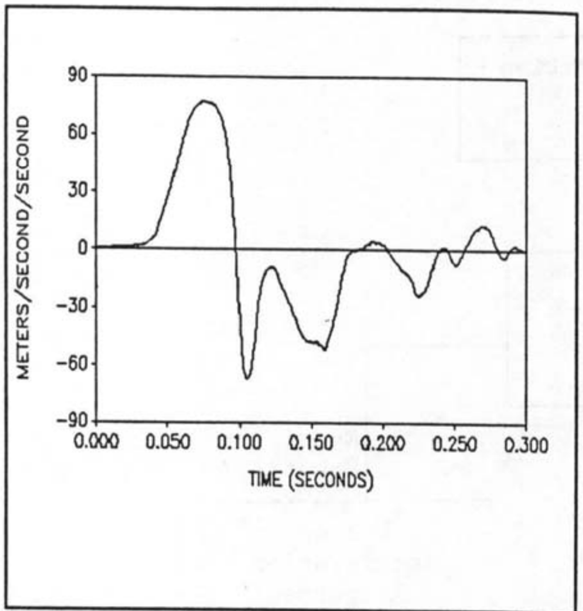


Figure 3. X-component of head linear acceleration in the sled coordinate system.

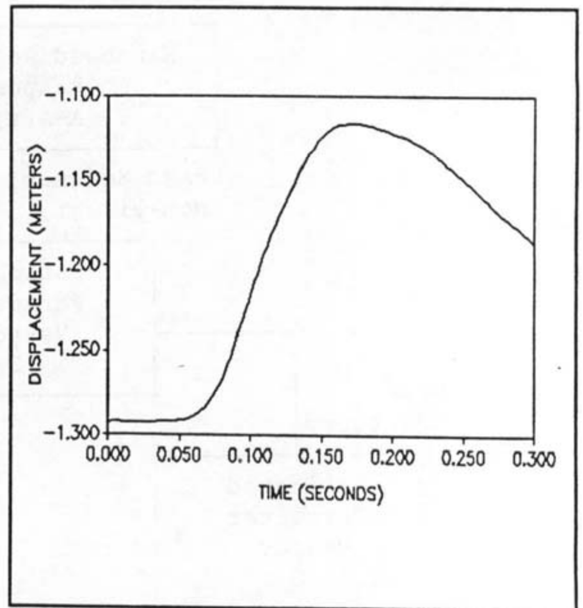


Figure 4. X-component of head linear displacement in the sled coordinate system.

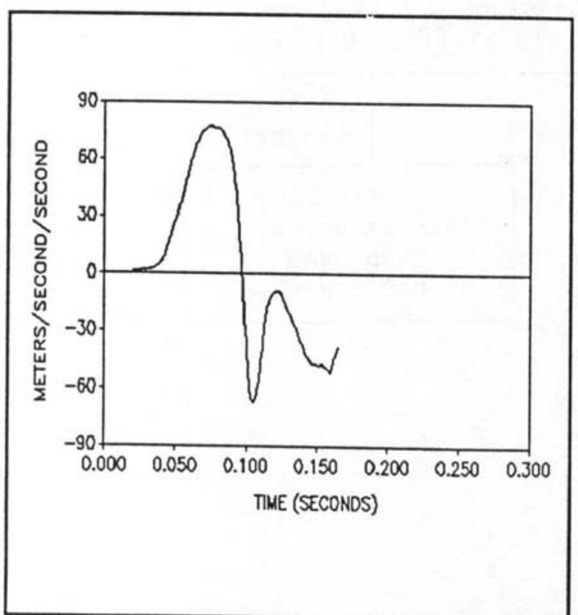


Figure 5. Windowed X-component of head linear acceleration in the sled coordinate system.

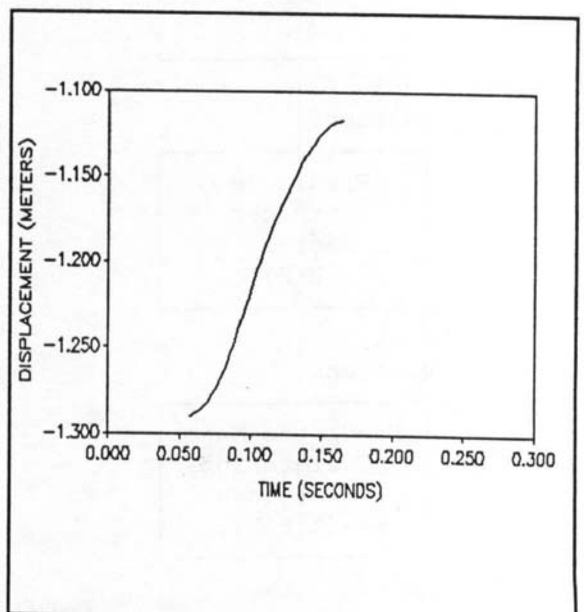


Figure 6. Windowed X-component of head linear displacement in the sled coordinate system.

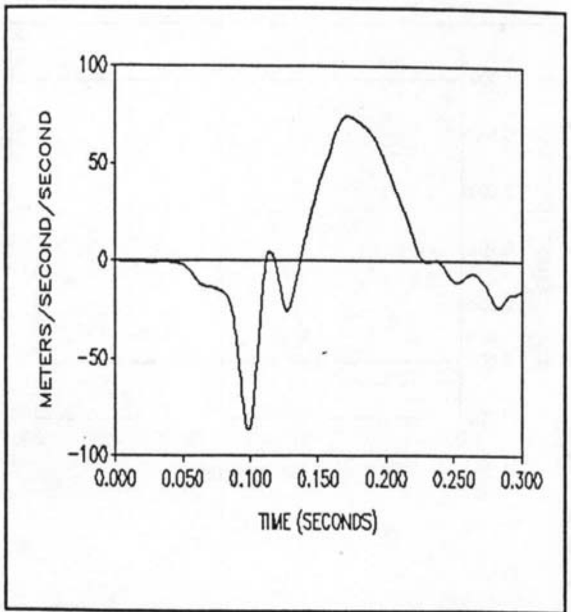


Figure 7. Z-component of head linear acceleration in the sled coordinate system.

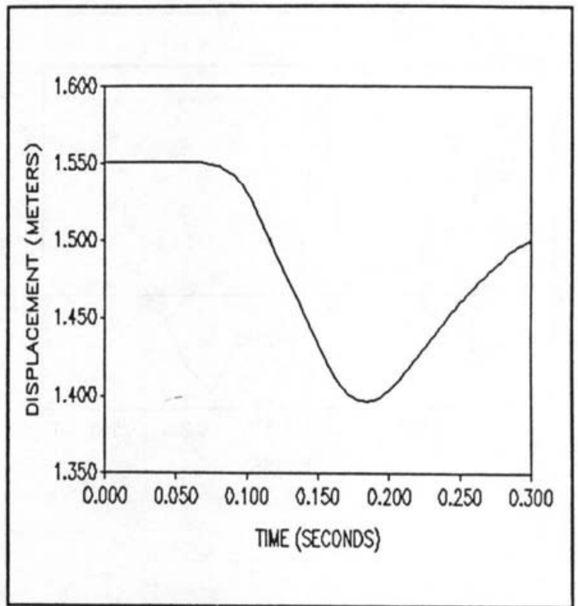


Figure 8. Z-component of head linear displacement in the sled coordinate system.

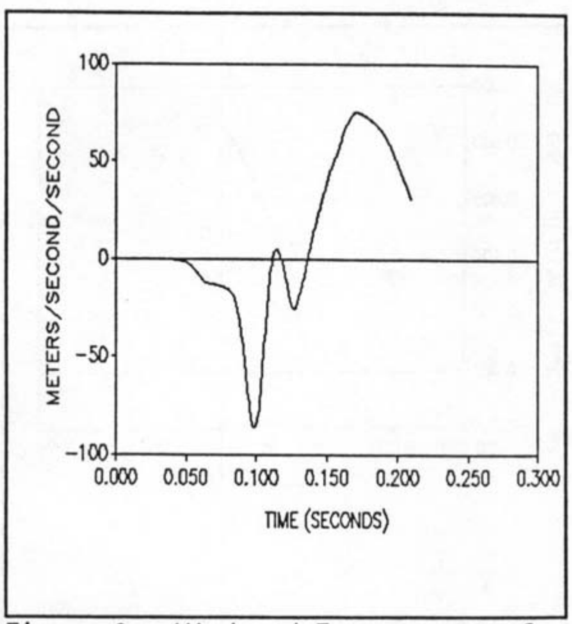


Figure 9. Windowed Z-component of head linear acceleration in the sled coordinate system.

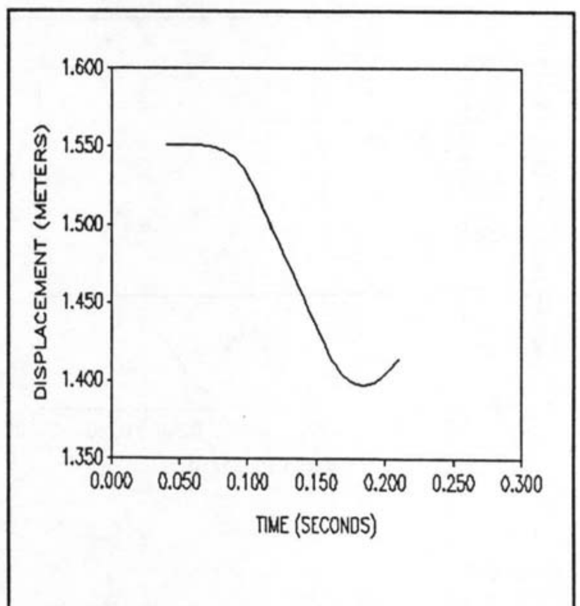


Figure 10. Windowed Z-component of head linear displacement in the sled coordinate system.

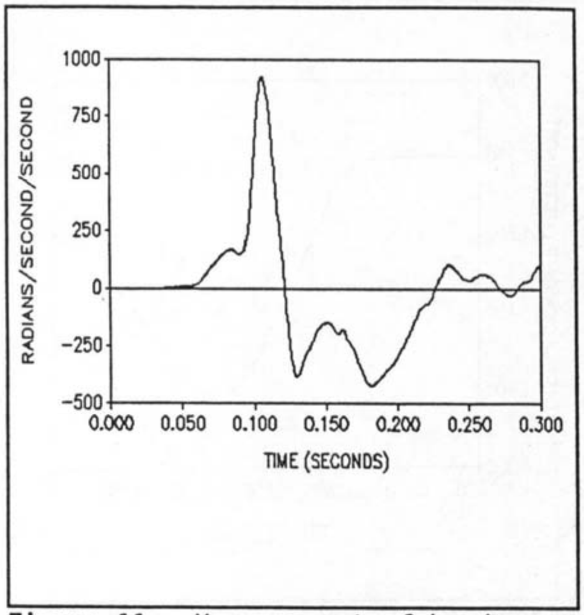


Figure 11. Y-component of head angular acceleration in the head anatomical coordinate system.

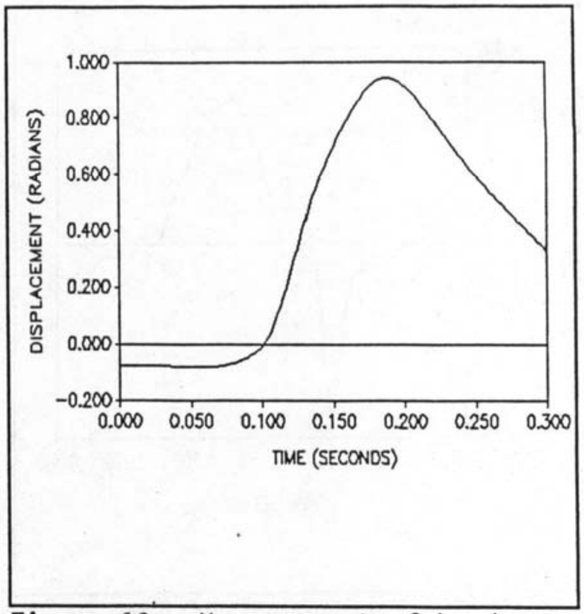


Figure 12. Y-component of head angular displacement in the head anatomical coordinate system.

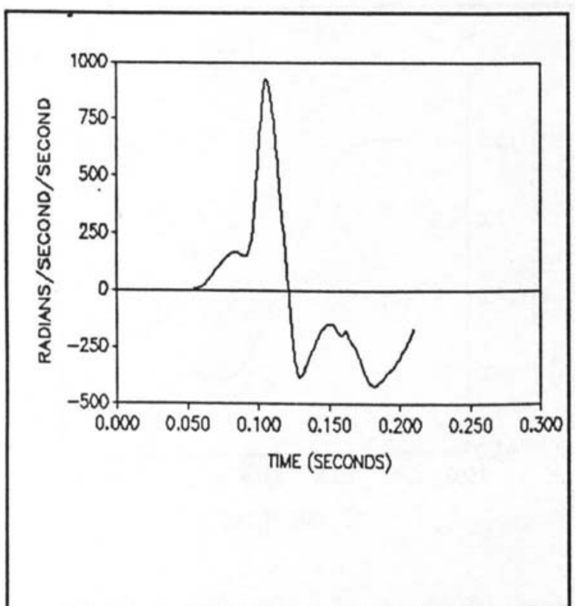


Figure 13. Windowed Y-component of head angular acceleration in the head anatomical coordinate system.

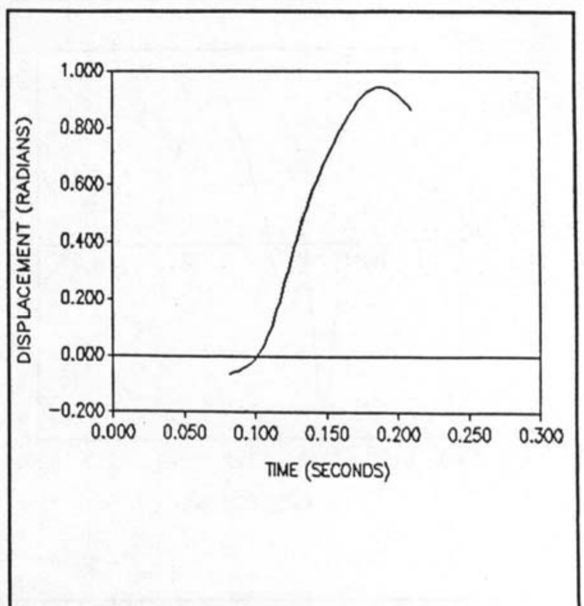


Figure 14. Windowed Y-component of head angular displacement in the head anatomical coordinate system.

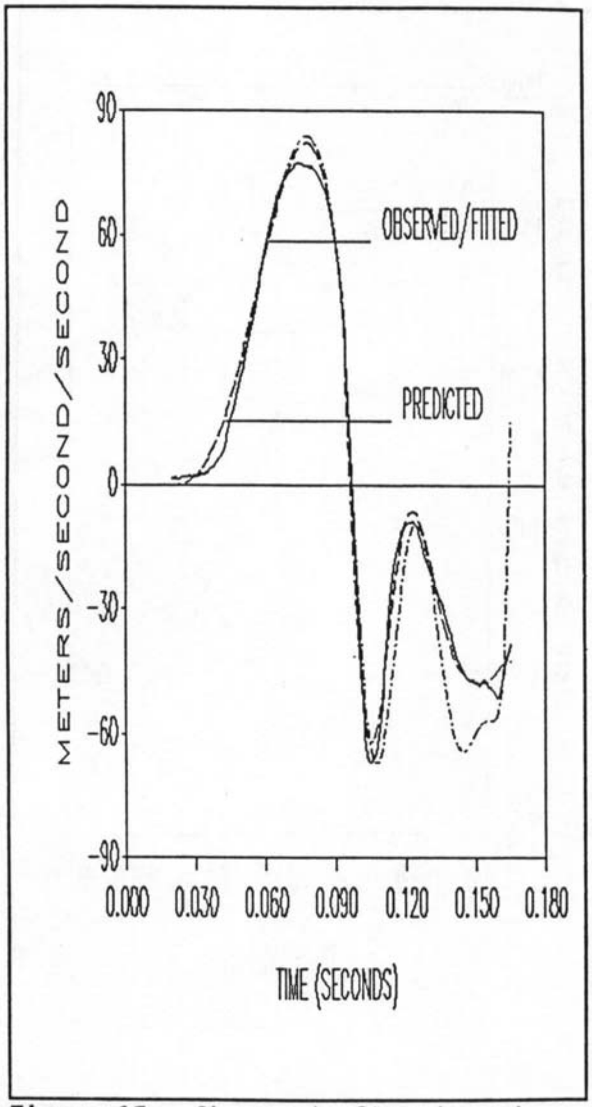


Figure 15. Observed, fitted, and predicted X-component of head linear acceleration in the sled coordinate system.

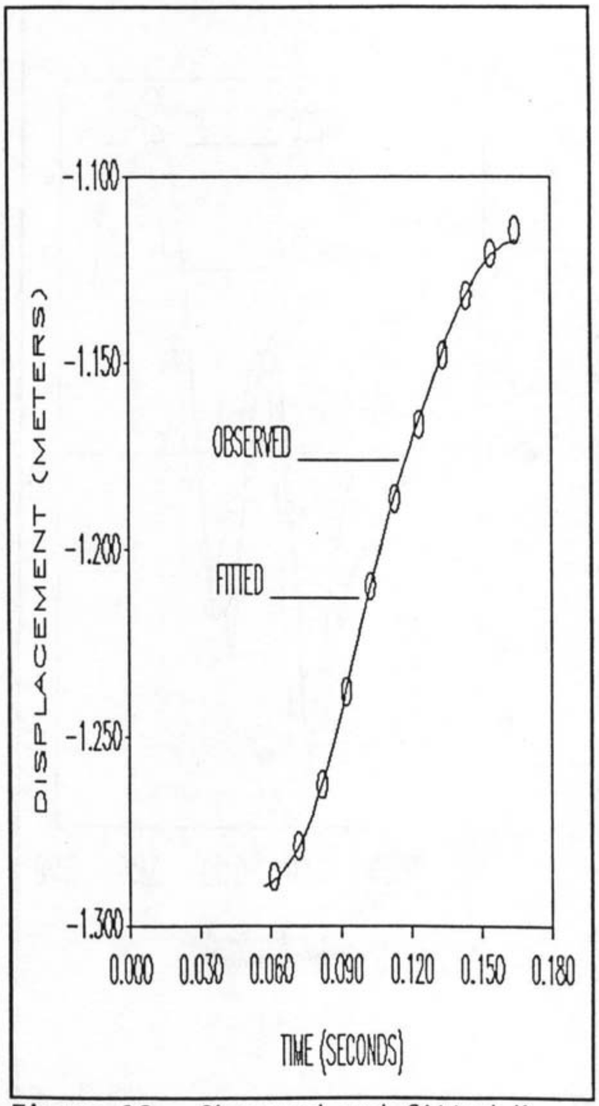


Figure 16. Observed and fitted X component of head linear displacement in the sled coordinate system.

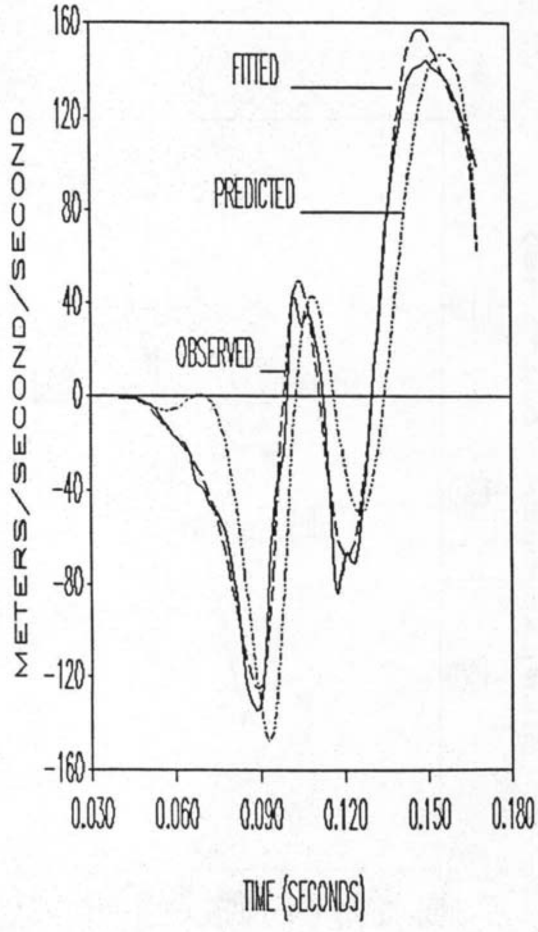


Figure 17. Observed, fitted, and predicted Z-component of head linear acceleration in the sled coordinate system.

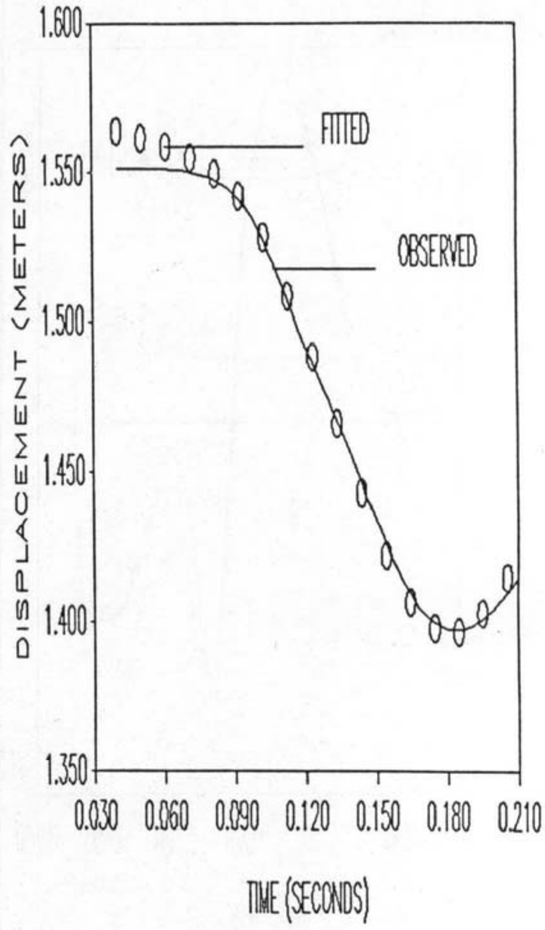


Figure 18. Observed and fitted Z-component of head linear displacement in the sled coordinate system.

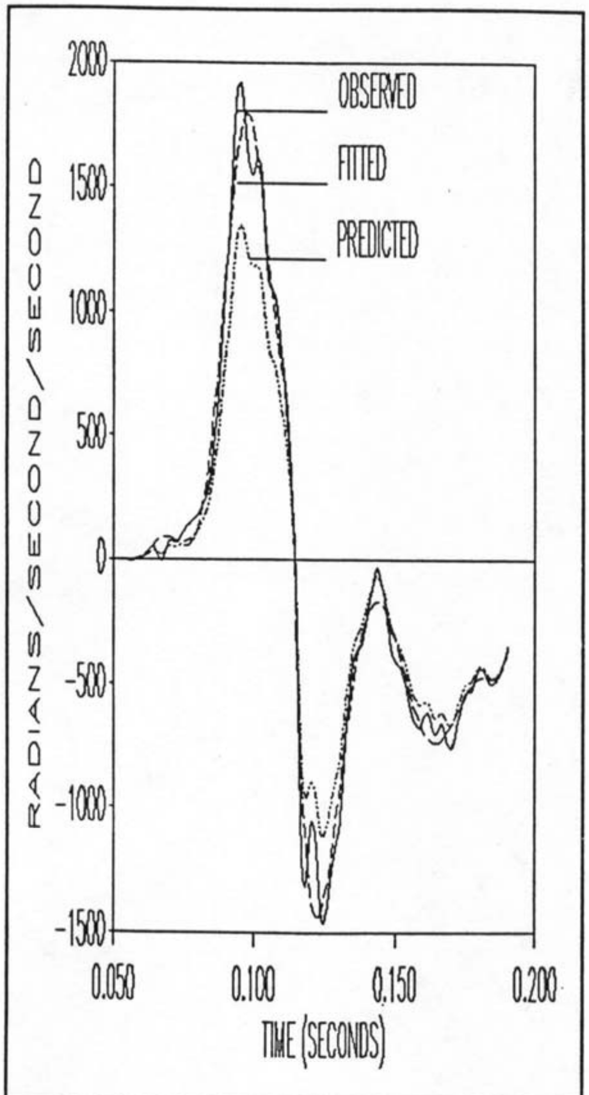


Figure 19. Observed, fitted, and predicted Y-component of head angular acceleration in the head anatomical coordinate system

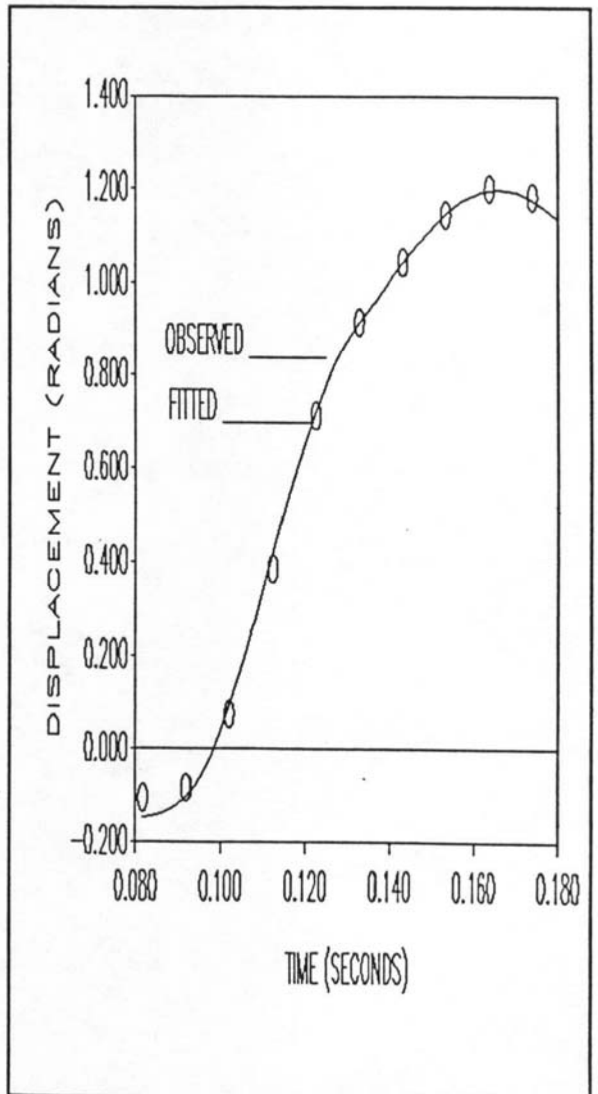


Figure 20. Observed and fitted Y-component of head angular displacement in the head anatomical coordinate system.