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MATHEMATICAL MODELING OF THE HYBRID III MANIKIN HEAD-NECK STRUCTURE

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Abstract. This paper presents results of an ongoing research program to develop data sets for mathematical models which accurately predict the head-neck kinematics and dynamics of anthropomorphic dummies in crash environments. The mathematical model utilized for this research was the Head-Spine Model (HSM), which was developed at the Armstrong Aeromedical Research Laboratory. In this study, the goal was to develop HSM data sets for the Hybrid III manikin head-neck structure. Modifications of the program source code were made in order to model the asymmetric bending properties of the neck. Data sets were developed, utilizing a 1-element and 4-element neck. The effect of the occipital condyle nodding block joint on head-neck kinematics and dynamics was also investigated and modeled. Tests were conducted to measure the stiffness of this joint in flexion and extension. A data set with a 1-element neck and nodding joint was developed. The Amended Part 572 Head-Neck Pendulum Test, of the Code of Federal Regulations, was simulated to validate these data sets. Small differences were observed between the responses of the 1-element and 4-element necks. The effect of nodding joint on head-neck kinematics and dynamics was negligible. Overall, the model proved to be a reasonable predictor of manikin head-neck kinematics and dynamics.

Keywords. manikin; head-neck kinematics and dynamics; matrix structural analysis computer programming

INTRODUCTION

In recent years, there has been an increasing awareness of the serious consequences that can occur with head and neck injuries and the effectiveness of biomechanical studies to reduce the likelihood of these injuries. Two sources of information about head and neck injury and prevention are: (1) accident simulations using mathematical models; and (2) experiments with human surrogates. Mathematical modeling is an accepted technique of scientific research. Once validated by comparison with experimental results, mathematical models are useful, economical, and versatile engineering tools. They can, in lieu of direct experimentation with the actual physical systems, evaluate the effects of varying parameters on the responses of systems to a wide variety of input conditions. It is hoped that the ability to predict manikin head-neck responses will help in the development of a more biofidelic manikin head-neck system and in the understanding of the responses of humans in similar environments.

For the past year, research has been conducted, with the Armstrong Aeromedical Research Laboratory (AAMRL) at Wright-Patterson Air Force Base, to develop data sets for computer models which accurately predict the head-neck kinematics and dynamics of anthropomorphic dummies in crash environments. In a previous study (Doherty and Paver, 1986), a data set of the Hybrid II manikin head-neck system was developed for the Head-Spine Model (HSM). The Part 572 Head-Neck Pendulum Test, of the Code of Federal Regulations, was simulated to validate this data set.

In this study, the goal was to develop HSM data sets for the Hybrid III manikin head-neck structure. To accomplish this goal, modifications of the program source code were made in order to model the asymmetric bending properties of the neck in flexion and in extension. Two data sets were developed. One data set utilized a 1-element neck; the second data set utilized a 4-element neck. The effect the occipital condyle nodding block joint on head-neck kinematics and dynamics was also investigated and modeled. Static and dynamic tests were conducted to measure the stiffness of this joint in flexion and extension. A data set with a 1-element neck and nodding joint was developed. The Amended Part 572 Head-Neck Pendulum Test, of the Code of Federal Regulations, was simulated to validate these data sets.

BACKGROUND

The Hybrid III Head-Neck Structure

The Hybrid III manikin is a state-of-the-art biofidelic anthropomorphic dummy. The head is a hollow two-piece casting of 356-T6 aluminum with a vinyl skin cover. The neck, which consists of aluminum and asymmetric butyl rubber layers with a central steel cable, exhibits different mechanical responses in flexion and extension. A load cell and occipital condyle joint, with butyl rubber nodding blocks, connect the head and neck. An adjustable steel bracket connects the neck and pendulum.

The Head-Neck Pendulum Test

Calibration test procedures and performance standards for the Hybrid III manikin are described in the *Code of Federal Regulations*, Part 572 Amended. The head-neck test consists of a pendulum drop. At the bottom of the pendulum's swing, the arm impacts a block of honeycomb; this produces a near square-wave pendulum deceleration pulse. The head-neck system, which is mounted to the end of the pendulum, undergoes no impact. Both flexion and extension tests are required. The specifications for the head-neck mounting position and the strike plate deceleration pulse and impact velocity differ for flexion and extension. There are two ways that the response is specified: (1) Head rotation vs. time; and (2) Moment about the occipital condyles vs. time. Ranges of amplitudes and times are specified for the peak values and ranges of times are specified for the zero crossings.

The Head-Spine Model

A variety of mathematical models have been developed to predict human biodynamic responses and injury potential in impact environments. The use of these models is an accepted and complementary research approach to direct experimentation with humans, animals, and manikens. The mathematical model utilized for this research was the Head-Spine Model (HSM), developed at AAMRL. This model has been successfully implemented for several military applications (e.g., the dynamic responses of head-spine subsystems to +Gz accelerations).

The HSM is a three-dimensional matrix structural analysis computer program (Belytschko et al., 1976). It is an internal body structure type model, which deals with the detailed structure of various body subsystems and predicts stresses, strains, localized deformations, and injury potential. The human body is represented by a collection of rigid bodies connected by deformable elements. The deformable elements can be beam elements, spring elements, hydrodynamic elements, or elastic surfaces. The program integrates the equations of motion in time explicitly. The analysis accommodates large displacements and small strains of the rigid bodies, nonlinear stiffnesses, and viscous (percent critical) and structural damping forces.

It is the data set, the input to the program, that defines the structure to be represented. In general, an HSM data set consists of 6 types of input: (1) the coordinate system definitions; (2) the geometry of the nodes and connectivity data; (3) the boundary conditions and constraints on the motion; (4) the inertial properties of the rigid bodies and deformable elements; (5) the material properties of the deformable elements; and (6) the excitation and initial conditions.

METHODS AND RESULTS

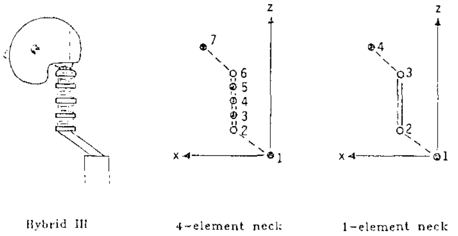
Program Modifications

Modifications were made in the program source code in order to model the asymmetric bending properties of the neck in the A-P plane. Different stiffnesses can be input for positive and negative bending and positive and negative torsion of the beam elements.

Description of the Data Sets

Several HSM data sets of the Hybrid III head-neck system were developed. The Amended Part 572 head-neck pendulum compliance test was simulated to validate these data sets.

Figure 1 shows the discretization of the Hybrid III head-neck structure. The coordinate system was defined so that the positive x, y, and z axes were the A-P, L-R, and S-I directions, respectively. During an actual test, the pendulum arm only rotates about the y axis. Since the response is specified from the time of impact to the time the head returns to the pre-impact position, it was assumed that the end of the pendulum (i.e., node 1) does not rotate. The motion of this point was modeled as a pure translation in the x direction; no translations in the y and z directions or rotations about the x or z axes were allowed for this point. All other points were allowed to translate and rotate in the x-z plane.



Hybrid III 4-element neck 1-element neck

FIG. 1. Discretization of the Head-Neck Structure

As a preliminary effort, the details of the construction of the Hybrid III neck were not explicitly modeled. The head was represented by a rigid body. The neck was represented by a spinal disc beam deformable element (i.e., a Kelvin solid with linear stiffness and viscous damping). The dark circles show the locations of the lumped masses of the rigid bodies (i.e., the primary nodes). The open circles show the locations of the secondary nodes. The dotted lines represent rigid links between the primary and secondary nodes. The shaded bar represents the deformable element. The pendulum was not explicitly defined. The boundary conditions at node 1 were made to reflect the presence of the pendulum and the constraints of the experimental design.

The geometric and inertial properties of the head and neck were derived from GM design specifications. The values used initially for the bending stiffness and damping of the neck were derived from results of a study conducted by AAMRL and Systems Research Laboratories for the Department of Transportation. Ranges for the stiffness were calculated from the measured static and dynamic stiffnesses of two Hybrid III necks. The shear parameter and the axial and torsional stiffnesses and damping of the neck were derived from the bending parameters and appropriate geometrical considerations.

Next, the layered aluminum/butyl rubber construction of the neck was incorporated into the Hybrid III data set. The 1-element neck was divided into four rigid bodies connected by beam elements. Each aluminum disc was represented by a rigid body. Each rubber disc was represented by a beam element. Masses and moments of inertia of the rubber discs were lumped at the head center of gravity (cg) or the cg's of the aluminum discs. The bending stiffnesses and shear parameters of the 4-element neck, which are length sensitive, were scaled from values used for the 1-element neck.

The excitation for the model, applied at node 1, was the specified pendulum strike plate deceleration profile. The initial conditions, which were the velocities of the primary nodes, were calculated from the specified pendulum strike plate impact velocity.

Simulation Results

The original data sets were tuned to make the model responses comply with the performance standards. Since the geometric and inertial properties of the Hybrid III head and neck are well documented, these constants remained fixed; they were not used to tune the data set. The material properties of the neck, however, are not well documented. The bending properties of the neck were varied within the ranges of the experimental static and dynamic test data. By varying these properties in a systematic manner, optimization of the model response with the specifications was possible (see Table 1).

The flexion test was simulated using the 1-element and 4-element neck data sets. Figure 2 shows the model excitation and the specified pendulum strike plate velocity for this simulation. Figure 3 is a plot of the head rotation vs. time. Figure 4 is a plot of the moment at the occipital condyles vs. time. The dashed line is the response of the 1-element neck. The solid line is the response of the 4-element neck. Differences were observed between the responses of the 1-element and 4-element neck data sets: (1) the 4-element neck exhibited a slightly larger peak rotation than the 1-element neck; and (2) the 1-element neck exhibited a larger peak moment. The periods of rotation and moment were similar for both data sets.

The extension test was simulated using the 1-element and 4-element neck data sets. Figure 5 shows the model excitation and the specified pendulum strike plate velocity. Note that the peak deceleration level and impact velocity is lower for the extension test than for the flexion test. Figure 6 is a plot of the head rotation vs. time. Figure 7 is a plot of the moment at the occipital condyles vs. time. The dashed line is the response of the 1-element neck. The solid line is the response of the 4-element neck. Differences were observed between the responses of the 1-element and 4-element neck data sets: (1) the 4-element neck exhibited a larger peak rotation than the 1-element neck; and (2) the 4-element neck exhibited a slightly larger peak moment. The periods of rotation and moment were slightly longer for the 4-element neck.

Table 1. Hybrid III Material Properties

1-Element Neck Stiffnesses

axial: 9.000×10^9 *dynes/cm*
torsional: 5.594×10^9 *dyne − cm*
bending: 8.000×10^8 *dyne − cm* (flex)
3.550×10^8 *dyne − cm* (ext)

Other 1-Element Neck Parameters

shear parameter: 5
axial damping: 0.2%
bending damping: 0.2%

4-Element Neck Stiffnesses

axial: 875.6×10^6 *dynes/cm*
torsional: 5.594×10^9 *dyne − cm*
bending: 4.500×10^9 *dyne − cm* (flex)
2.000×10^9 *dyne − cm* (ext)

Other 4-Element Neck Parameters

shear parameter: 125
axial damping: 0.2%
bending damping: 0.2%

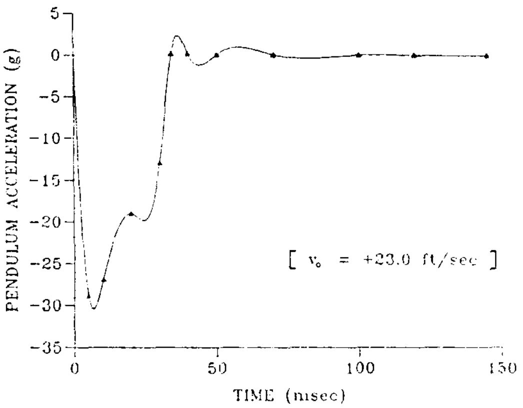


FIG. 2. Model Excitation (Flexion Test)

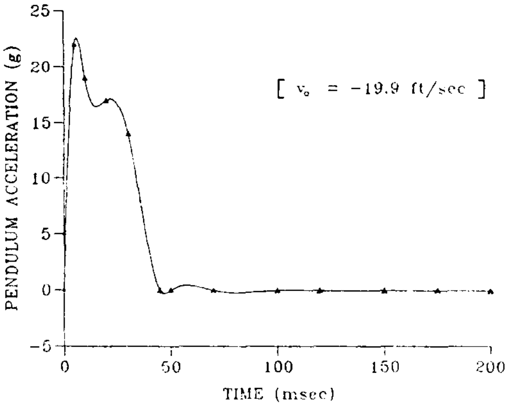


FIG. 5. Model Excitation (Extension Test)

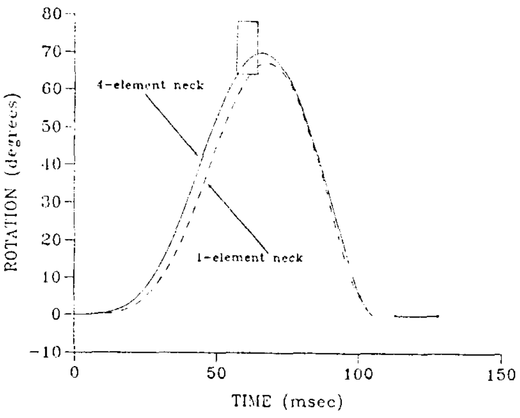


FIG. 3. Head Rotation (Flexion Test)

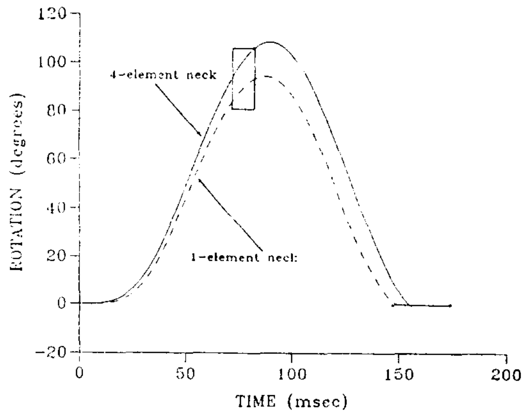


FIG. 6. Head Rotation (Extension Test)

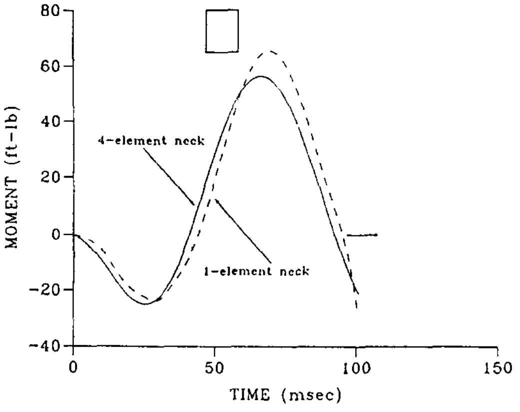


FIG. 4. Neck Moment (Flexion Test)

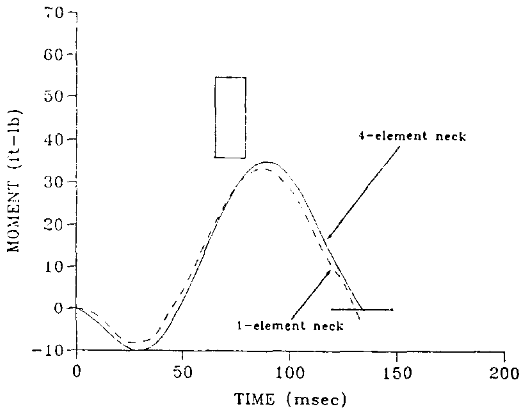


FIG. 7. Neck Moment (Extension Test)

Nodding Joint Stiffness Tests

Static and dynamic nodding joint stiffness tests were performed. The joint was mounted horizontally for the static tests. The neck endplate was fixed and a moment arm was attached to the top of the load cell. Moments were applied by hanging weights at the end of the moment arm. The moment and rotation at the end of the moment arm were measured. Small differences were observed between the flexion and extension stiffnesses. For the dynamic tests, the joint and moment arm were mounted vertically. A weight was rigidly attached to the end of the moment arm. Either a force was applied to the weight or the weight was displaced and released. The moment-time histories were recorded. The system was analyzed as a torsional pendulum (i.e., the joint stiffness was calculated from the frequency of the vibration). Differences were observed between the static and dynamic stiffnesses. Further studies are being conducted.

Nodding Joint Data Set Description

The 1-element neck data set was modified to incorporate the occipital condyle nodding block joint into the neck description. Basically, this joint acts like a torsional spring; the spring stiffness is due to the rubber nodding blocks within the joint. Since there is no torsional spring element in the HSM code, the joint was represented by a suitable modification of the beam element.

Figure 8 shows the geometry of the nodding joint. The physical descriptions of the system are shown on the left; the model descriptions are shown on the right. The two shaded horizontal links represent the joint, essentially two beams on their sides. These beams are compliant only in torsion. As a preliminary effort, the measured static stiffnesses were utilized for these simulations. The values were approximately one order of magnitude larger than the bending stiffness of the 1-element neck.

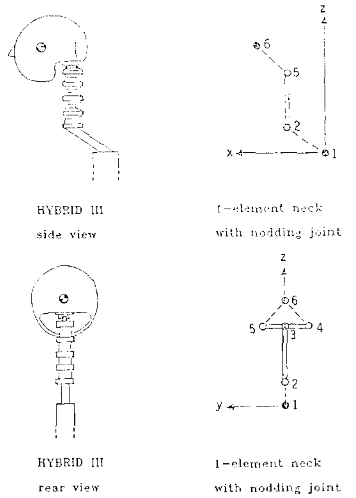


FIG. 8. Nodding Joint Geometry

Simulation Results

Simulations were performed, using the 1-element neck with the nodding joint, and compared to previous results. Figures 9-10 show the flexion response. Similar results were obtained for the simulation of the extension test. The dashed line illustrates the response of the 1-element neck without the nodding joint. The solid line illustrates the response of the 1-element neck with the nodding joint. Figure 9 is a plot of the head rotation vs. time. The differences, at the beginning of the simulation and at the peak rotation, were slight. Figure 10 is a plot of the moment at the occipital condyles vs. time. The occipital condyle nodding block joint had little effect on the response.

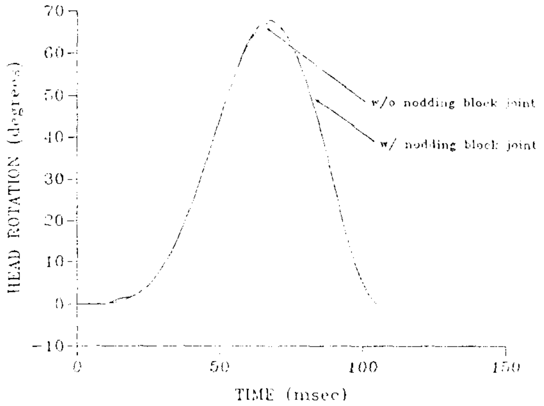


FIG. 9. Effect of Nodding Joint on Head Rotation (Flexion Test)

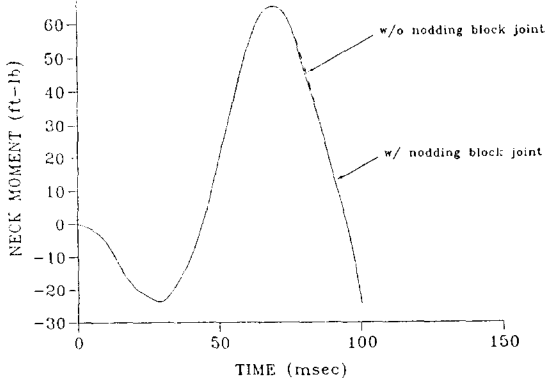


FIG. 10. Effect of Nodding Joint on Neck Moment (Flexion Test)

Execution Times

Table 2 shows the approximate CPU times required for typical simulation runs on a MICROVAX II.

Table 2. Execution Times for Typical Simulations

SIMULATION	CPU TIME
1-element neck w/o joint	appx. 2 min
4-element neck w/o joint	appx. 2 hr
1-element neck w/ joint	min. 20 hrs

SUMMARY

1. Modifications were made in the program source code in order to model the asymmetric bending properties of the neck in flexion and extension.

2. Data sets of the Hybrid III maniken head-neck system were developed for the Head-Spine Model. The Amended Part 572 Head-Neck Pendulum Test was simulated to validate these data sets. Small differences were observed between the responses of the 1-element and 4-element necks. The model proved to be a reasonable predictor of the maniken head-neck kinematics and dynamics.

3. Tests were conducted to measure the stiffness of the occipital condyle nodding block joint in flexion and extension. Data sets were modified to incorporate this joint. The Pendulum Test simulations indicated that its effect on Hybrid III maniken head-neck kinematics and dynamics is negligible.

RECOMMENDATIONS FOR FUTURE WORK

The following are recommendations for future work:

1. Conduct tests to measure the stiffness and damping of a single Hybrid III neck element in order to verify the bending parameters used for the 4-element neck

2. Conduct additional static and dynamic tests and simulations of the nodding joint

3. Modify the program source code to incorporate a true torsional element

4. Continue tuning the proposed Hybrid III data sets by additional validation studies

5. Compare dummy responses with human volunteer and cadaver data to assess the biofidelity of these systems in test modes other than flexion and extension.

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