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Bioman—An Improved Occupant-Crew Station Compliance Modeling System

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GEORG D. FRISCH and LOUIS A. D'AULERIO

Naval Aerospace Medical Research Laboratory, Detachment 1, Michoud Station, New Orleans, Louisiana 70189, and Aircraft and Crew Systems Technology Directorate, Naval Air Development Center, Warminster, Pennsylvania 18974

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The need to visualize and interpret human body movement data from experiments and simulations has led to the development of a computerized, three-dimensional representation of the human body and crew station. While conventional charts and graphs can be used to follow movements of individual body parts, it has been our experience that only by observing the entire movement of the various body segments can experimental results be integrated with simulation studies. Such a process requires that program output be used to animate a realistically formed and jointed human body model incorporated within an existing or projected crew station. Animations are essential whenever the volume of data collected or generated is too great to assimilate piecemeal, or when the complexity of the motion under study leads to visualization difficulties in a two-dimensional graph. Dissatisfaction with existing body models and stick figure displays led to the development of a new human and crew station model for the computer with distinct advantages in display realism, movement definition, collision or interaction detection, and cost-effectiveness in a real-time animation play-back environment. Development of this program was meant to provide an improved method for evaluating the physical compatibility of crew members with crew stations under all types of G environments.

EVALUATION OF THE PHYSICAL compatibility of crew members with crew stations has traditionally been based on anthropological, environmental, and task sequence data. With today's sophisticated aircraft, the ability of crew members to perform under adverse conditions is becoming increasingly crucial making the man-machine interface an extremely important design consideration. Unfortunately, evaluation techniques of man's performance have not kept pace with the evolution of aircraft design. Physical compatibility of man and machine must be evaluated not only in terms of physical and visual interface but also in terms of reach and clearance envelopes. Techniques, such as drawing reviews, mockups, flight simulators, prototype flight, and track tests, are important and produce useful data but suffer from the limitation of not being able to take into account the full variability in crew anthropometry and environmental factors. Mathematical models have produced some additional significant insight into the problems, but their usage has been limited due to their complexity, lack of evaluation criteria, and the inability to get an adequate data base which can be used to validate evaluation results.

When analyzing crew station geometry, two apparently distinct types of mathematical models have emerged. The first deals with the human factors aspect of the problem as opposed to those whose primary concern is the biodynamic response of crew members to acceleration forces generated by aircraft maneuvers or catastrophic events such as ditching, crashes, and ejections (1-7). Although logically compatible, results from these two sources have not been adequately correlated or used interactively due to the lack of standardization of input data, methodologies employed, format, and output descriptors.

A complete evaluation of a given crew station must consider not only the ability of a crew member to perform his tasks but also assure that the crew station geometry does not pose a problem during emergency egress. Information gained from gross body motion simulation, i.e. movement of body segments in response to applied forces, should be used to revise clearance and reach envelopes, which in turn could significantly alter the placement of crucial controls or cockpit geometry in general.

SCOPE

In formulating the graphics model presented here, the primary consideration was ease of usage and generality in application. The intent was not to reformulate capabilities of existing models but, rather, to develop a tool which would use data generated by these programs as input for further analysis. The bulk of the data analyzed by this laboratory consists of human dynamic response data, simulation results (pirmarily based on the Calspan Program discussed later), and dummy and hardware testing programs conducted at the Naval Air Development Center, Naval Air Engineering Center, and Naval Weapons Center. The computer program was structured in such a fashion that human response data, simulation results, and test track and ejection tower test data could

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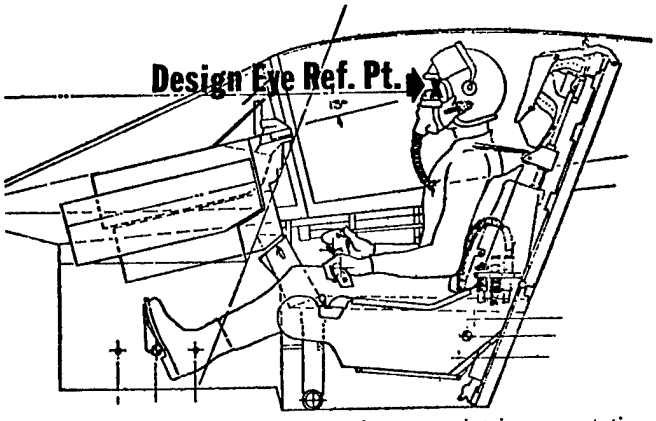

Fig. 1. Location of design eye reference point in crew station.

be used as inputs, and be compared on a common basis in terms of man-machine interface.

Injuries to aircraft crews must be viewed in terms of limitations of the escape system, as distinguished from inadequate crew station geometry. Injuries due to the first classification are usually a result of high-G forces and inadequate restraint, whereas injuries due to the latter can be related to direct impact between body segments and the crew station interior. Of the two, direct impact injuries are easier to prevent and all available data should be used to define clearance envelopes required.

The two major areas of simulation to be incorporated consist of crew station geometry and occupant dynamics. Computer programs considered as sources of input to this model are briefly discussed below under the classification to which they pertain.

CREW STATION GEOMETRY

The Cockpit Geometry Evaluation Computer Program System (CGECPS) was used to check and transform digitized crew station data (1). In our application of the program, two reference systems were used. The first is the design coordinate system (using buttock, water, and station lines), where the cockpit plane vertices and control locations are expressed in this reference system using crew station drawings. The data are then transformed to a Euclidean coordinate system (X,Y,Z) with the origin at the design eye reference point (Fig. 1). Before each evaluation run, the occupant's eye midpoint (defined in the head coordinate system) was made coincident with the design eye reference point origin. The crew member's anthropometry and seating position was used to define seat pan location, which was then checked against the allowable seat adjustment range. If within range, an ideal initial seating position was defined (i.e. crew member seated at the design eye reference point) and the simulation was ready to proceed. Exceeding the seat adjustment range defines a problem of accommodation. Permissible seat adjustment values were then used (together with the seating position data) to redefine a new eye reference point (as distinguished from the design eye reference point) and all cockpit information was transformed to this new origin.

It is important to remember that several types of inputs can be used to drive the occupant segments and, consequently, determine initial positions. If dynamic test data are used (sled and tower tests using dummies), then link lengths, joint ranges, weights of segments, and other initial position data are determined from the test conditions. The primary aim of such a simulation is to detect possible strikes between occupant segments and crew station interior. This type of analysis is used primarily for validation purposes where one is looking for replication of motion monitored and analyzes this motion within the constraints of the crew station configuration. Since control locations have been defined in terms of the eye reference point, the CGECPS program can be used to determine initial angular orientation of occupant segments, given that certain controls are being contacted. This can be accomplished in terms of general anthropometric categories or for specific dimensional data under investigation.

Human test data are treated in a similar fashion. Experiments conducted at the Naval Aerospace Medical Research Laboratory Detachment monitored head and neck motion in response to acceleration, using both inertial instrumentation and high-speed photography (8). Locations of the head and T1 (first thoracic vertebral body) coordinate system origins are determined throughout the entire course of the run (Fig. 2). The graphics representation of the head and neck system can now be driven using human data and analyzed in terms of the crew station geometry. The midpoint of the infraorbital notches, defined in the head anatomical coordinate system, is placed at the design eye reference point, and the monitored head and neck motion can be analyzed in terms of the crew station dimensions. There are two significant factors that must be kept in mind. The first is that only head and neck positions are known and, consequently, only head interference can be detected. Secondly, initial position is predetermined by the test configuration. Seatback angles in human tests are somewhat

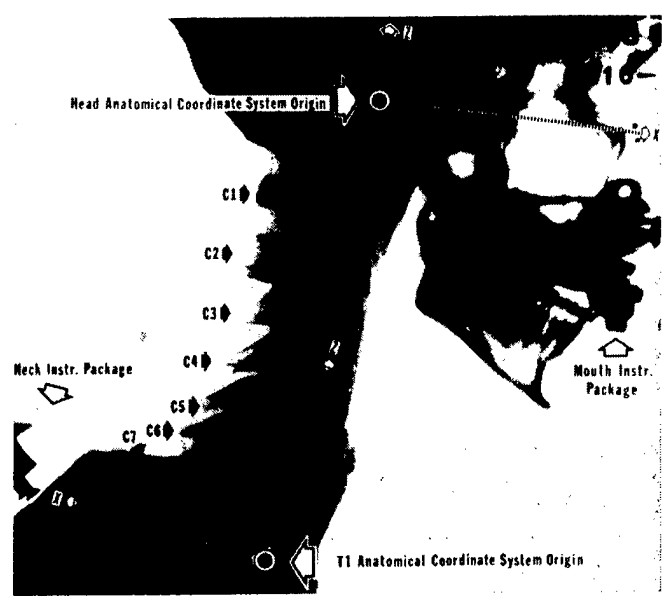

Fig. 2. Definition of head and neck anatomical coordinate systems. Note the location of mouth and neck instrumentation packages.

different, as is the restraint system employed. Human test subjects are much better restrained than a pilot would be flying a particular aircraft. Both of these factors could significantly affect clearance envelopes. Results, however, could be interpreted as representative of a best-case situation (i.e. perfectly restrained, sitting at the design eye reference point). One can vary the initial position of the occupant and restraint system parameters using the simulation program discussed below.

OCCUPANT MOTION SIMULATION

Having the crew station data and seat time history (either monitored or simulated), the man-machine interface under G can now be analyzed. If human data are used and initial conditions of the aircraft can be related to those of the human test (no angular velocity on the seat), then the human data can be used directly in evaluating the crew station design. However, as mentioned previously, only head and neck data are presently available and one must resort to simulation if information on other segments or other test situations is desired. Dummy test data can also be used directly for the specific test conditions available. To expand the data base to include other conditions, simulation must again be considered.

The program routinely used to simulate occupant response is the Calspan Simulator (4), which has been the subject of several validation papers by the authors (9-11). The model is quite flexible and modular in design, so that the complete range of anthropometric variation, weight distribution, moment of inertia of segments, and joint-limiting angles can be handled effectively. The occupant can be modeled by up to 20 segments, connected by 19 joints. The inclusion of tension elements and spring dampers facilitates the representation of muscles and ligaments, and flexible elements such as the neck can be handled with relative ease. The complete flexibility in anthropometric dimensioning, together with the ability of specifying omnidirectional input and dynamic initial conditions, make this program an ideal tool for evaluating the occupant-crew station compatibility under acceleration. Segment-segment and segment-crew station contacts are also monitored and evaluated in terms of forces generated. Modifications to the original version include evaluation of the effects of belt interactions and windblast forces.

One can, in fact, drive any segment and make the simulation as simple or as complex as desired. For example, if one is only concerned with head clearance, and

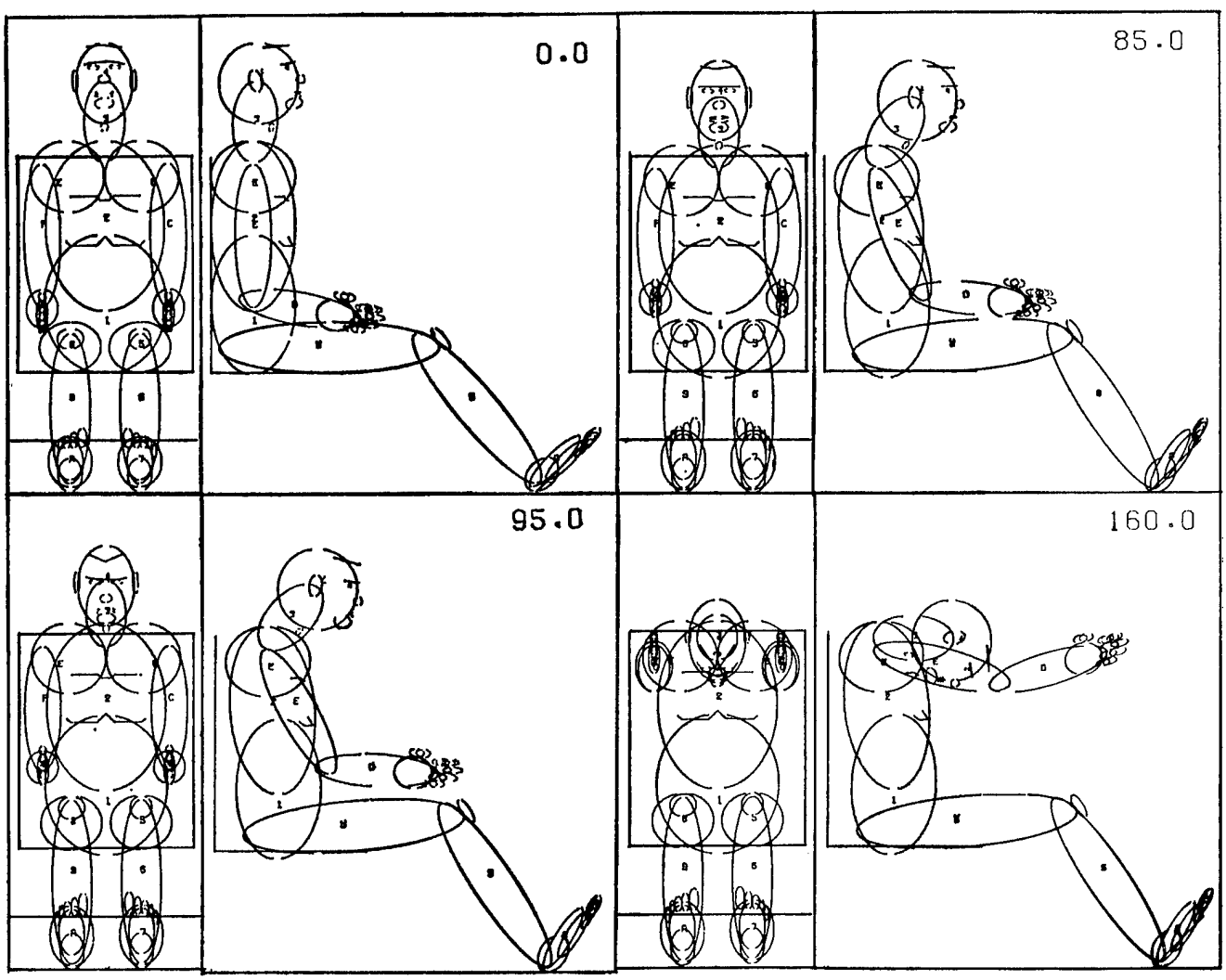

Fig. 3. Ellipsoidal respresentation of crew member using program output as driving function.

the time history of T1 is known, then only the head and neck system need be driven using the T1 anatomical coordinate system origin as the locus where the acceleration is applied. In most dummy tests, the head is hinged to the upper torso via a rigid neck and consequently constrained to move in the midsaggital plane. However, the forces applied are such that yawing and rolling of the head would result if the constraints were removed. In such a case, if the location of the neck pivot in relation to the dummy's 3-D instrumentation is known, then an acceleration profile for this pivot point is easily calculated and can be used to drive a revised head-neck system. One can also model all segments according to the restrictions of the test and allow the head the freedom of motion warranted. Incremental changes to input parameters can also be investigated in terms of their contribution to simulation precision.

ANTHROPOMETRY

Options for different graphical representations of the human body are provided, their usage depending on the complexity desired and likelihood of strikes occurring. The Calspan program provides optional output of segment time histories and contact ellipsoid information. Each segment is modeled via an ellipsoid, whose origin (in relation to the segment C.G. location) and force deformation properties are specified (Fig. 3). Use of this package greatly facilitates interpretation of data and can be used as a preprocessor to isolate specific crew station surfaces with which contact might occur. As an example, previous ejection simulation results can be used to define segment motion in the inertial reference frame. Analyzing this motion within the confines of a specific crew station will isolate the areas of concern. A full simulation, employing the exact seat time history and initial conditions of the aircraft, together with the pilot's initial position within the crew station, can then be undertaken. Only those crew station surfaces previously isolated need be included in the interference checks conducted during simulation, greatly reducing the computer costs involved. The entire crew station can still be plotted and visual checks undertaken to assure that, in fact, only those surfaces stipulated need to be monitored.

To increase the resolution by attaining a better representation of the human form, a refinement of anthropometric representation was recently undertaken, employing the methodology of the Biostereometrics Laboratory, Baylor College of Medicine, from whom a data set was gratefully obtained (12) (Fig. 4). Using a three-dimensional photographic technique, the topography of the subject is established in the inertial reference frame, as are the locations of up to 80 bony skeletal landmarks. The resulting data base consists of successive slices, each one having a common Z level and a defined center of gravity. This center of gravity constitutes the average of coordinates of all points of the cross section. The number of slices required for simulation input is a function of resolution sought. As an example, Fig. 4A contains twice as many data points as 4B. From the bony landmarks, the anthropometric dimensions of the subject can be established and the location of the joints estimated. These joint locations determine the skeletal structure and segment lengths. Segment orientations are calculated from the data and the various slices, or partial slices, assigned to the segments modeled (Fig. 5). Fig. 5A through 5M demonstrate this assignment, where 5A constitutes the head, 5B head and neck, 5C head, neck, and shoulder, etc. In articulating this body, each

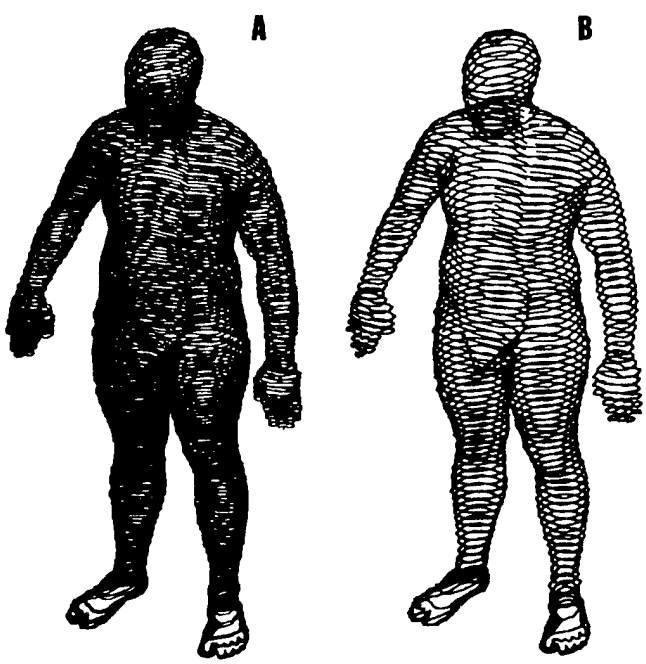

Fig. 4. Contour data representation of crew member. From location of bony landmarks, joint locations and segment lengths are estimated. Increase in resolution is a function of number of data points used. A) consists of twice as many points as B).

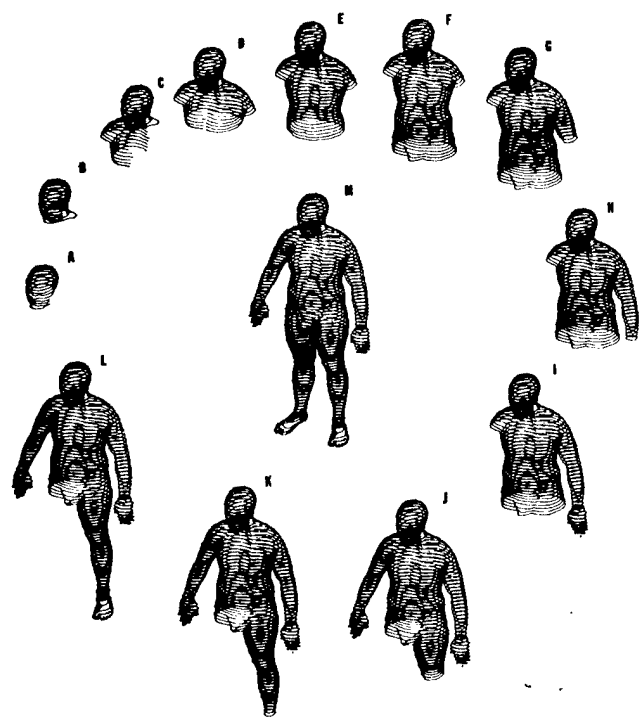

Fig. 5. Segmentation of contour data. A) head only; B) head and neck; C) head, neck, and right shoulder; D) head, neck and thorax; E) inclusion of abdominal region; F) inclusion of lumbar region; G) inclusion of upper arm; etc.

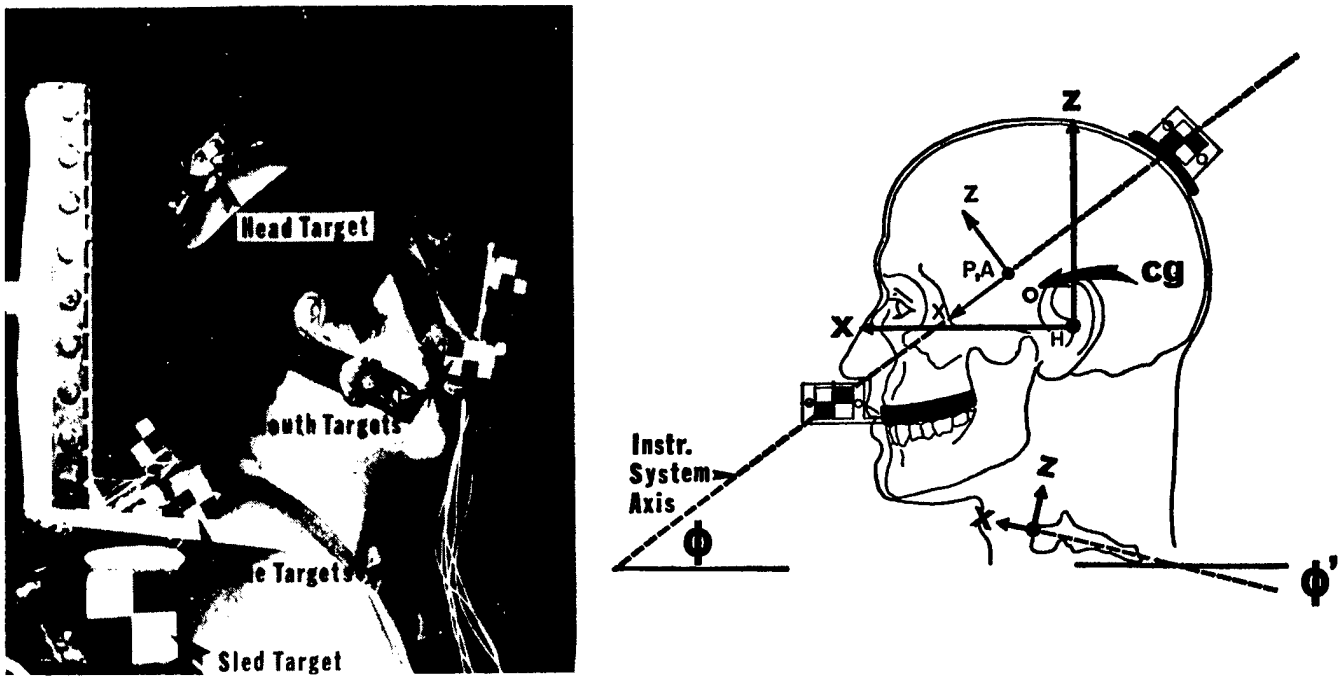

Fig. 6. Localization of photographic targets to head and neck anatomical coordinate systems.

slice and the defined joints must be transformed into the segment local coordinate system (i.e. in terms of the segment C.G. locations). Initially, these C.G. locations are estimated from anthropometric dimensions but, as better estimates become available, the slice transformations can be easily recalculated. As before, the entire skeletal structure, or portions thereof, can be driven either under computer control or using monitored human data.

The advantage of this topographic method is that a permanent record is attained which can be redigitized if more data points are needed. Additionally, locations of nonbony skeletal landmarks can also be defined. X-ray anthropometry of all human subjects tested at NAMRL Detachment is used to localize photographic targets and inertial instrumentation relative to the head and neck anatomical coordinate systems (Fig. 6). If three-dimensional photography is taken with the mounts in place, the location of these coordinate systems in the inertial reference frame can then be established. As in the elliptical representation, it is a relatively simple task to dimension the data to accommodate various anthropometric categories. Changes in link lengths, keeping the number of slices the same, will result in the spacing between each successive slice being increased, and vice versa. Increasing or decreasing the size of the slices themselves is accomplished by defining a vector extending from the center of gravity of a slice to each point constituting the outline. Upward or downward scaling of the vector lengths is used to redefine the location of these outline points.

No matter how precise the definition of the human body, clearance envelopes and the possibility of contact are directly related to equipment worn by crew members. Serious injuries to the head, resulting from direct contact, must be viewed in terms of head-helmet displacement within the crew station. Even under the assumption that the helmet does not move relative to the head, which itself can cause serious injuries, the increase of the volume represented by the helmet must be accounted for. Although digitized information on various helmets is readily available, relating these data to the head coordinate system must be repeatable and consistent. A preliminary experiment was conducted using a medium HGU-35P helmet and phantom head (human skull covered with rubber material to simulate features) in which the head anatomical coordinate system was defined. Lead pellets were attached to the left and right center of rotation points of the helmet, as well as to the middle of the front trim line. The helmet was then placed

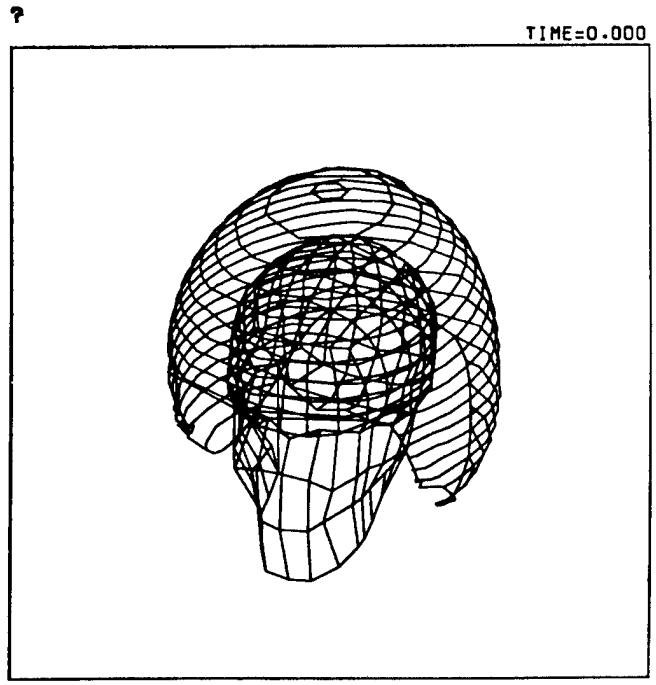

Fig. 7. Helmet contour data defined on digitized skull.

on the marked phantom head and X-rays were taken. The XY plane of the helmet coordinate system was defined by the three lead markers and the Z axis was taken as normal to this plane, with its origin midway between the two center of rotation pellets. The original helmet data, expressed in terms of water, buttock, and station lines, were transformed to the above defined helmet coordinate system. The location of the helmet coordinate system origin was defined on the head anatomical coordinate system from the X-ray data. The helmet shell contour data were then retransformed to the head coordinate system. Fig. 7 illustrates the increase in volume attributable to the helmet. It should be pointed out that, although a definition of a helmet coordinate system is necessary for proper localization of helmet contour data on the head anatomical coordinate system, the one chosen need not be considered as ideal, and another can be substituted as long as it can be repeatedly defined (using the same landmarks) across helmet types. Further experiments are planned to determine the repeatability with which a subject can place the helmet on his head and the variability, across subjects, of helmet contour locations on the head coordinate system. Since mouth mount locations are defined relative to the head coordinate system, subjects wearing these mounts and helmets can be analyzed using photographic techniques. This eliminates the necessity for nonmedical use of X-rays.

Since many applications of head dynamic response data do not consider a protected head, it was deemed necessary to provide a program option in which precise head data could be displayed independently of other body segments. Clearly, if a helmeted head strikes an object, the precision necessary to describe the skull outline need not be that high, as long as the helmet contours are localized on the head coordinate system. It is, after all, the helmet that will make contact. With the unhelmeted head, however, precision is required to establish the existence and location of contact and the dynamic conditions existing at the time. The digitized skull information, employing the same coordinate system previously described, was obtained from T. A. Shugar's Finite Element Head Injury Model (13). Although at present not representative of any particular anthropometric categorization, the computer input library can be expanded as additional information becomes available. Head contour data obtained from stereo photography (Fig. 5A) can also be used since it was redefined in terms of the head anatomical coordinate system. This system was estimated from the location of the auditory meatus and infraorbital notches. The head-helmet data can again be driven by either computer simulation results or by human head trajectory data.

Care must be taken when analyzing helmeted head trajectories using human data as input. The trajectories monitored are those of human, unhelmeted subjects, suitably restrained, with a seatback angle of 90°. Displaying this motion within the cockpit (Fig. 8 left), with the initial position determined via the methodology previously described, provides significant insight into the crew station-pilot compatability. Range of motion under less restrictive restraint will, in all probability, be increased and, therefore, results from human data tend to be on the optimistic side. Inclusion of a helmet (Fig. 8 right) expands the displacement volume and increases the likelihood of contact. The additional weight of the helmet, and its effect on the head trajectory, has as of yet not been properly defined. The effect, however, is expected to be detrimental in terms of increasing head range of motion. Viewed from this perspective, results obtained must be considered as the best-case situation and that in actual situations the hazard would be increased.

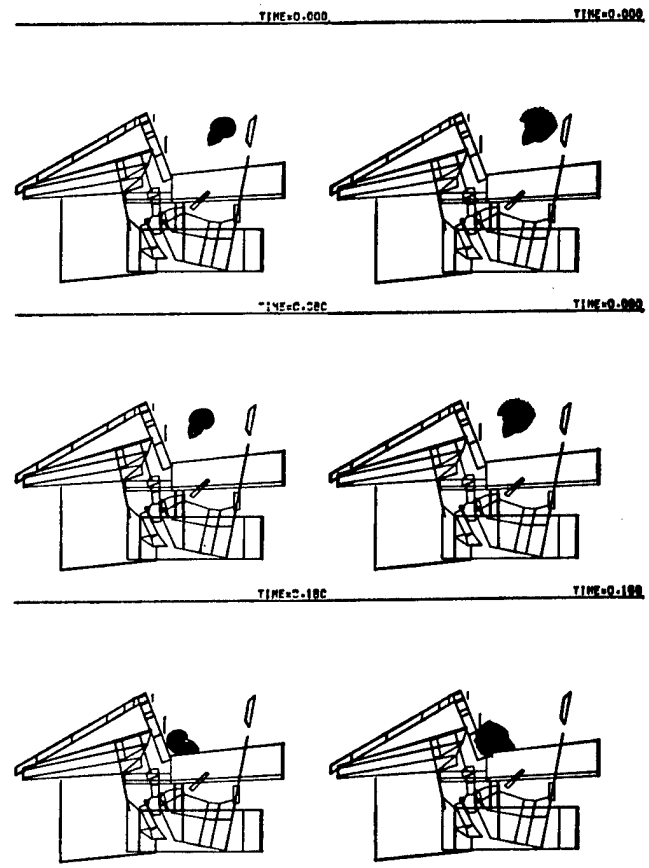

Fig. 8. Head displacement within the A-7E crew station. (Human data 12 G, 535 G/s onset). Note increase of clearance required with the addition of helmet (right).

APPLICATIONS

The graphics package described was designed not only to handle various sources of input but also to be flexible enough to provide the best possible insight into results. As such, the object observed can be viewed from any position (as if a camera were placed there) using any perspective desired. Enlargement or reduction can also be specified as required. Since occupant response to an omnidirectional input can be simulated, applications to specific test or accident situations become self evident. Ejections, carrier arrested landings, and ditchings can be investigated in some detail. Typical deceleration profiles of carrier landings are available and data, when transformed to the crew station from its original locus, can be used to drive the crew station model. The same holds true if accelerations seen during ditching are ever

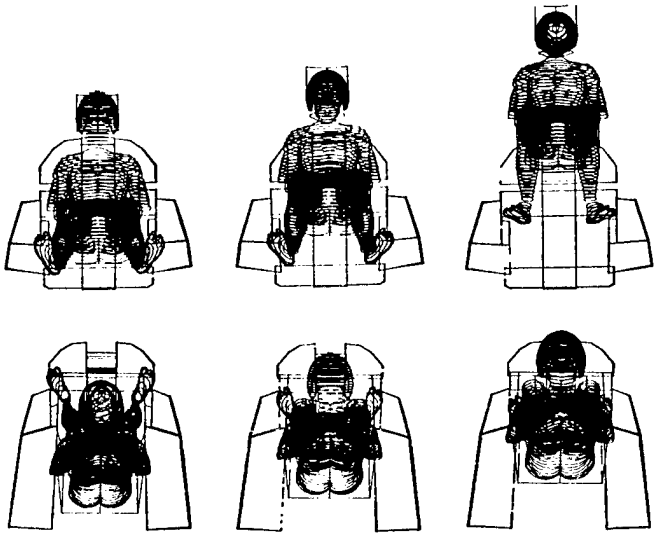

Fig. 9. Simulation of carrier arrested landing with seat belt failure.

quantified. If the resulting data from these two sources can be correlated to that monitored during human tests, then human data can be used directly to drive the head within the crew station. In such situations, all possibility of contact must be eliminated. There is no sense in providing elaborate underwater escape systems if the crew member is unable to activate them as a result of unconsciousness sustained from direct impact.

An example of the complexity that can be obtained is demonstrated in Fig. 9 where a carrier arrested landing with seat belt failure is simulated. Although not representative of any test or accident, it does demonstrate the fidelity that can be obtained. In this particular example, the feet were not constrained by the rudder pedals, although this interaction can be specified with obviously altered foot and lower leg orientations. For this figure, the A-7E crew station was employed with top and front views shown for three time periods (0.0, 0.12, and 0.15 s into the deceleration).

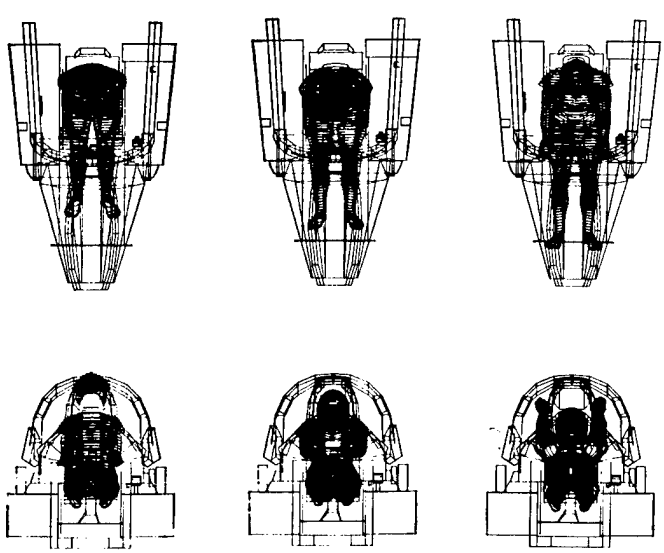

Fig. 10. F-18 ejection simulation.

Fig. 10 shows an ejection from an F-18 cockpit using representative acceleration time histories. The top portion of the figure shows a view from the area of the rudder pedals looking up at the pilot whereas, in the lower portion, the observer is looking down over the shoulders into the crew station. The program was used to analyze occupant-crew station compliance during ejection from the proposed F-18 crew station and a foot-instrument panel contact problem was isolated and confirmed from track and tower tests. A detailed report of this work is presently being prepared for publication in the immediate future.

Since the viewing location can be specified to be at the eye reference point, the pilot's perspective of the crew station interior can be used as a design tool. Control locations can be manipulated, using graphics, so that ease of pilot viewing and activation, when necessary, can be maximized. This should be done before crew station prototypes are ever constructed. Additionally, aircraft carrier flight decks can be digitized and, for given aircraft time histories, the pilot's view during landing can be displayed.

Crew station geometry can be expanded to include any enclosure, such as automobile interiors. Usually, in such cases, greater clearance is provided and the effects of various seating and restraint arrangements can be investigated. If direct contact is detected (using the skull representation provided) results can also be used directly as inputs to a finite element head injury model.

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