HUMAN BODY SIMULATIONS FOR ANALYSIS OF AIRCRAFT CRASH SURVIVABILITY

by

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Introduction

There are three major considerations in designing crashworthiness into a vehicle structure whether the vehicle is to be used on land or in the air. The first is to ensure that sufficient living space is maintained during impact. The second is to restrain the occupants to prevent injurious contact with the vehicle interior or ejection from the vehicle; implicit in this requirement is the need to retain the seat in the vehicle as well as keep the occupant in the seat. The third is to attenuate the forces experienced by the occupant to a tolerable level.

The aircraft crash environment presents problems that can make protection of occupants particularly difficult. For example, the peak vertical acceleration present in a crash may exceed the level that the human body can tolerate in a direction parallel to the spine without injury. In light aircraft it is generally not practical to design sufficient energy-absorbing capability into the lower airframe structure to protect the occupant against these vertical forces, as the prerequisite crush space is not available. Including some mechanism for energy absorption in the seat structure of such an aircraft could reduce occupant injury in a crash. However, not only does prediction of the seat structure response to dynamic loading present a complex engineering problem, but gross overall deformation of the seat further complicates restraint system design in most light aircraft where the lap or shoulder belts are often attached to the aircraft structure. Because dynamic interaction of the seat, occupant, and restraint system is too complex for analysis by manual techniques, the design process should be supported by computer simulation, although final evaluation of a crashworthy design must include full-scale dynamic testing.

This paper will review specific requirements for both mathematical and mechanical models in the evaluation of aircraft seating and restraint systems, and present a three-dimensional mathematical simulation of the human body, which has been developed primarily for analysis of aircraft crash survivability.

Evaluation of Aircraft Seating Systems

Design principles and criteria for aircraft seats and restraint systems are presented in the Aircraft Crash Survival Design Guide (1)*, which was originally published in 1967 and has been updated several times. The most recent revision includes results of more than a decade's research and design experience. It describes desirable strength and deformation characteristics, material selection, attachment to the airframe structure, cushion properties, energy-absorbing

*Numbers in parentheses indicate references listed at end of paper.

mechanisms, restraint system configurations and characteristics, and means for system evaluation by analysis and testing.

Criteria for crashworthiness are also concisely stated in a military specification, MIL-S-58095 (2). Key requirements pertaining to crashworthiness are minimum static strengths and limits on the seat's load-deformation characteristics in the longitudinal, lateral, and vertical directions. Provision must be made for energy absorption in the vertical direction, and the energy-absorbing mechanism is required to protect occupants ranging in size between the 5th and 95th percentiles from experiencing accelerations in excess of human tolerance. An obvious problem in designing for the two extremes of occupant weight is to provide sufficient stroking distance for the 95th percentile while ensuring that the 5th percentile, utilizing a shorter stroke distance, will not suffer excessive acceleration. The specified compromise sets the energy absorber limit load for a static load factor of 14.5 G, based on the combined weight of the 50th-percentile occupant and movable part of the seat.

The performance of a seat designed in accordance with MIL-S-58095 is evaluated by means of six static tests and two dynamic tests. Both dynamic tests utilize a 95th-percentile anthropomorphic dummy and are conducted according to the conditions illustrated in Fig. 1. Both demonstrate the structural integrity of the seat under simulated crash conditions. Furthermore, in the first test the energy-absorbing mechanism is required to maintain the acceleration measured on the seat below a specific level. For example, the vertical acceleration component should be less than 23 G for durations in excess of 0.006 sec.

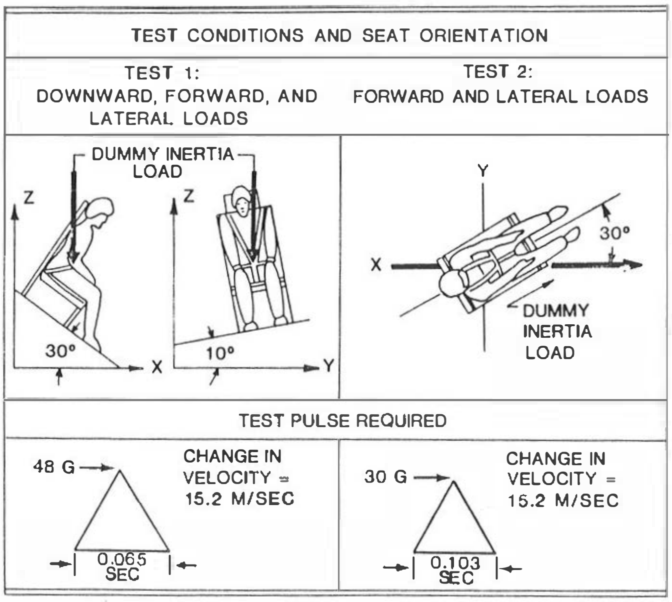

Fig. 1. Dynamic test requirements (2).

A shortcoming of the tolerance-based criterion lies in the fact that the measured response of the seat is a function of the dynamic characteristics of the coupled seat-occupant system, i.e., different occupant characteristics produce different seat response. Existing dummies probably provide a realistic test of seat and restraint system strength, but their characteristic dynamic response to vertical inputs has been shown to differ significantly from human response. An aviation test dummy, possessing more humanlike response to vertical input, and including some means for direct prediction of one or more injury modes, such as by a force transducer in the lumbar region, is needed.

Even when a dummy for aircraft use is available, such a device can only be employed practically in the evaluation of a completed design, and cannot replace mathematical simulations during development. Such simulations should, ideally, yield humanlike response regardless of the impact conditions. They should provide realistic estimates of loading on the seat and restraint system, as well as measuring injury potential in typical aircraft crash environments. The development of a computer simulation intended to achieve these goals is described in the following sections.

Mathematical Simulation for Crash Analyses

A number of dynamic models of the human body have been developed for crash survivability analysis. These models vary in complexity and possess from 1 to 40 degrees of freedom. One-dimensional models have been used in prediction of human body response to an ejection seat firing which, if the body is tightly restrained, can be approximated as a one-dimensional phenomenon. However, a vehicle crash generally involves a horizontal component of deceleration which forces rotation of body segments with respect to each other. If no lateral component of deceleration is present, a two-dimensional model will suffice, provided the restraint system is symmetrical. The diagonal shoulder belt that, combined with a lap belt, is often used in light aircraft is assymmetrical and may cause lateral motion of the occupant even in the absence of a lateral deceleration. Therefore, a model that is generally useful in restraint system evaluation must be capable of predicting three-dimensional motion, and several three-dimensional kinematic models, consisting of interconnected rigid links, have been developed (3-6). These models and several developed for predictions of head, spinal, and thoracic injury are discussed and compared in Ref. 7.

In 1972, the U.S. Department of Transportation, Federal Aviation Administration (FAA), initiated a program to provide a practical engineering tool for use in the design and evaluation of seats and restraint systems for light aircraft. This program incorporated a dynamic model of the human body combined with a finite element model of the seat structure, intended to enable the designer to analyze the structural elements of the seat as well as evaluate the dynamic response of the occupant during a crash. The digital computer program based on this model is called SOM-LA (Seat/Occupant Model - Light Aircraft). Because the goal in the development of this program was to assist engineers whose function is seat and/or restraint system design, a number of user-oriented features were included to facilitate operation by minimizing the quantity of input data required, particularly in regard to those data that might not be readily available to an engineer in the aircraft industry. For example, dimensions and inertial properties for "standard" occupants, a 50th-percentile human male and a 50th-percentile anthropomorphic test dummy, were included in the program so that they could be readily selected by the user.

This original model was described in a comprehensive technical report published by the FAA in 1975 (8). Modifications have been made to the model since then to improve simulation quality and to provide increased capability and additional desirable output. In that interim, a testing program was initiated by the FAA Civil Aeromedical Institute (CAMI) to provide data for validation of the model. Although work on model improvement and validation is continuing, the remainder of this paper will describe the present model, its validation, and success to date in modeling actual systems.

Seat/Occupant Mathematical Model

The occupant is modeled by eleven mass segments as illustrated in Fig. 2. The torso and head segments are connected by beam elements that possess axial, flexural, and torsional stiffness. The hip and shoulder joints are of the ball-and-socket type, each possessing three rotational degrees of freedom. The elbow,

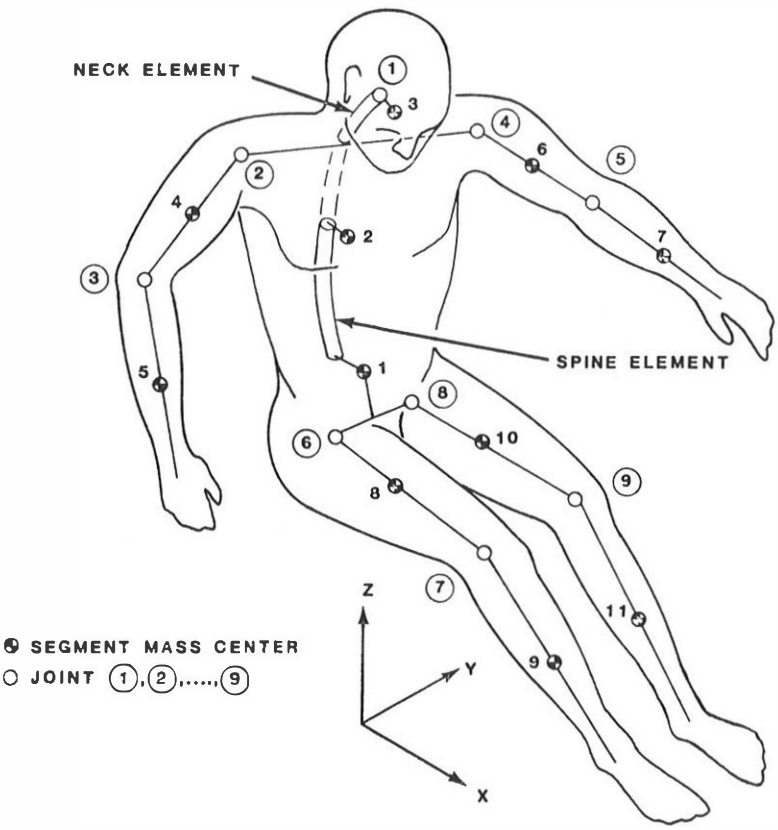

Fig. 2. Eleven-segment occupant model.

knee, and head-neck joints permit hinge-type motion. In total, the model possesses 31 degrees of freedom for simulation of a human subject. For simulation of a dummy, one degree of freedom is removed by locking the head-neck joint so that motion of the head relative to the torso is determined solely by deformation of the neck element.

Joint Resistance. Rotation of the body joints is controlled by viscous dampers and nonlinear torsional springs. The damping coefficient for each joint is constant in all cases, but the spring moments depend on the user's choice of human or dummy occupant. For simulation of a human occupant, they are zero throughout the normal range of joint rotation, but increase rapidly at the limiting angular displacements. For simulation of an anthropomorphic dummy, constant (nonzero) frictional moments are applied throughout the normal range of motion; these torques increase to higher values to limit the rotation, just as in the case of the human occupant.

External Forces. The external forces that act on the eleven body segments can be characterized as either contact forces or restraint forces. The contact forces are the forces exerted by the cushions, the floor, and an optional inflatable restraint. Each of these forces is calculated by first determining, from occupant displacement, the penetration of a rigid contact surface fixed to a body segment into either a cushion or the floor. Using this deformation, the force is then computed from a table of forces and deflections that is provided as input data. Effects of nonlinear unloading, hysteresis, and rate sensitivity are considered.

The method used in calculating the forces exerted on the body by the restraint system differs somewhat from that used for the contact forces. The principal difference is that the restraint forces do not act at any fixed points on the body, but, rather, the points of application depend on current belt geometry. The five available restraint system configurations consist of a lap belt alone or combined with a single diagonal belt, over either shoulder, or a double shoulder belt, which may include a lap belt tiedown strap. The restraint loads are transmitted to the occupant through ellipsoidal surfaces fixed to the upper and lower torso segments. The locations of the anchor points on either the seat or the airframe structure and of the buckle connection are determined by user input along with webbing properties. The effect of initial slack or preload in the system is considered.

For both the upper and lower torso restraints, the forces are determined in the same manner. First, the belt loads are calculated from the displacements of the torso surfaces relative to the anchor points. Then, the resultant force on each segment is calculated and applied at the point along the arc of contact between the belt and the ellipsoidal surface where the force is normal to the surface.

The capability of the belts to move relative to the torso surfaces allows simulation of "submarining" under the lap belt, an important consideration in design of a seat and restraint system.

Occupant Physical Properties. Because it has been assumed that the principal user of this program is interested chiefly in the seat or restraint system, a minimum of information is required to describe the occupant. Input data include the selection of human or dummy, the main difference being the joint model, as discussed earlier. The dimensions and inertial properties for "standard" occupants, a 50th-percentile civilian male and a 50th-percentile anthropomorphic dummy, are included in the program. The segment lengths, masses, center-of-mass locations, and moments of inertia for the human occupant model are based on cadaver data reported in Refs. 9-11, averaged and adjusted to approximate 50th-percentile values. Corresponding properties for the dummy model are based on the specifications of U.S. Federal Motor Vehicle Safety Standard 208, Part 572. Should a user wish to simulate a larger or smaller occupant, provision is made to input nonstandard properties.

For calculation of external forces exerted on the occupant by the seat cushions and restraint system and for prediction of impact between the occupant and the aircraft interior, 24 surfaces are defined on the body. These surfaces are ellipsoids, spheres, and cylinders, as shown in Fig. 3. The dimensions of these surfaces were obtained from an anthropometric study of the U.S. civilian population (12).

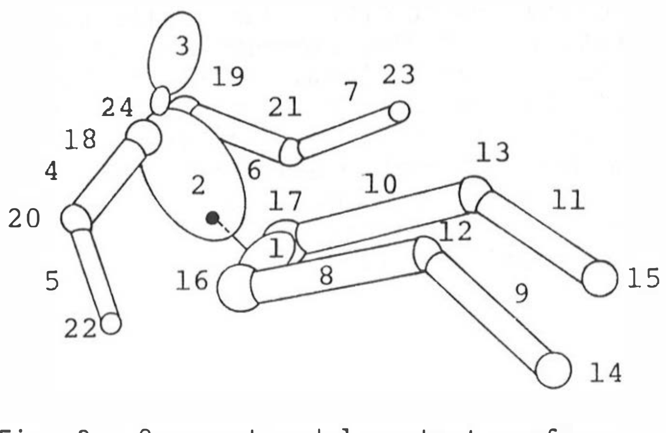

Fig. 3. Occupant model contact surfaces.

The ranges of joint rotation that are used in the program are based on the data of Dempster (9) and Glanville and Kreezer (13) for the human occupant and FMVSS 208 for the dummy. For joints where the allowed range of rotation was found to depend on the axis of rotation, the rotation about a lateral axis, which would predominate in a frontal impact, was considered most important and is used as the single limiting angle in the model.

Seat Model. The seat model uses a finite element analysis procedure that is based on explicit, timewise numerical integration of the equations of motion for the node points, as reported in Ref. 14. The technique permits analysis of the dynamic response of plate-beam structures involving very large displacements and rotations, as well as elastic-plastic material behavior. The capacity of the structural model is approximately 150 nodes, 150 elements, 5 materials, and 10 beam cross sections.

Because the solution step size for the structural analysis is governed by the frequency content of the finite element mesh, the inclusion of short, stiff elements may require a step size considerably smaller than that required for the occupant model. The computer program permits replacing such elements with rigid links, thereby permitting a larger step size and greatly improving efficiency.

For use in restraint system or cabin configuration analyses, where the details of seat response may be immaterial or seat design unknown, a rigid seat model can be selected. The rigid seat consists of only seat pan and back, which are fixed relative to the aircraft, and its use significantly reduces computer time required.

One type of seat that has been introduced in the crew stations of both civilian (15) and military (16) helicopters to achieve improved crash survivability is the guided energy-absorbing seat. The seat consists of a bucket to which the restraint system is attached and a frame mounted on the aircraft floor or bulkhead. Principal functional members of the frame are two vertical (or nearly vertical) guide tubes along which the bucket can move, controlled by one or more energy-absorbing devices. Vertical inertial crash loads force the seat bucket down the guide tubes against the resistance of the energy absorbers, producing an energy-absorbing stroke in that direction. For most efficient use of the stroke distance available between the bucket and the floor, energy absorbers have been designed to stroke at constant load, that load being determined by design criteria based on human tolerance to $+G_z$ acceleration. Assuming that for analysis of a guided seat under crash conditions the bucket and frame could be considered essentially rigid and all deformation concentrated in the energy-absorbing stroke, a stroking capability is included as a degree of freedom in the rigid seat option. Because elastic bending of the bucket and frame appear to influence seat and occupant response in dynamic testing, an additional degree of freedom was added to simulate rotational elasticity. The finite element model is capable of simulating such a seat, using spring elements for the energy absorbers, beams for the frame, and a combination of beams and plates for the bucket. However, such seats are typically designed with a frame of stiff, high-strength material, as significant deformation in the frame or bucket might impede the energy-absorbing stroke. The two-degree-of-freedom model can quite adequately simulate such a seat for a crashworthiness analysis. The detailed elastic response of the frame might then be more efficiently investigated using a general purpose, linear finite element model subjected to static equivalent loads determined from the dynamic analysis.

Digital Computer Program

The digital computer program based on the seat and occupant models is written entirely in FORTRAN IV to insure a high degree of compatibility with different computer systems, and during development it has been run on Control Data, IBM, and Univac systems.

Input data are read by the program in the following seven categories:

1. Simulation and output control information.
2. Cockpit description.
3. Cushion properties.
4. Restraint system description.
5. Crash conditions.
6. Seat design data.
7. Occupant description.

Output data consist of 10 blocks of information that are selected for printing by user input. The data include time histories of the following variables, which are stored during solution at predetermined print intervals for output in both digital and plot form:

1. Occupant segment positions (X, Y, Z, pitch, and roll).
2. Occupant segment velocities (X, Y, and Z).
3. Occupant segment accelerations (x, y, z, and resultants).
4. Restraint system loads (tensile loads in webbing and resultant normal loads on the pelvis and chest).
5. Cushion loads.
6. Aircraft displacement, velocity, and acceleration.
7. Displacements and stresses at selected nodes.
8. Floor reactions (forces and moments).
9. Contact between the occupant and the aircraft interior.
10. Injury criteria and axial force in the lumbar spine.

The injury criteria used in the program are all computed from segment accelerations. The Dynamic Response Index (DRI) provides an indication of the probability of spinal injury due to a vertical acceleration parallel to the spine (17). It is computed from the response of a single-degree-of-freedom, damped spring-mass model, which is driven by the component of pelvic acceleration parallel to the spine. The axial load in the lumbar spine is printed, as are the Severity Indexes (SI) for the chest and head, and the Head Injury Criterion (HIC) of Federal Motor Vehicle Safety Standard 208. Also, the predicted velocity and point of impact for contact between an occupant segment and the aircraft interior can provide information for design of energy-absorbing surface, including protective padding and collapsible structure under the padding.

Execution time for the program varies somewhat from one case to another because of its variable step size integration method, but typical times can be cited for a sample case. Simulation of a 15.2-m/sec impact like the drop test of MIL-S-58095 for an event time of 0.1 sec using the energy-absorbing rigid seat option has consumed from 24 to 60 sec of central processor time on a CDC Cyber 175 system using a three-dimensional solution. Using the optional two-dimensional solution reduces the required central processor time to between 4 and 8 sec for the same case.

Model Validation

Validation of the combined seat-occupant model has been based on a testing program conducted at the FAA Civil Aeromedical Institute (CAMI). The tests used an

Alderson VIP-50 dummy in a forward-facing test seat with a restraint system consisting of a lap belt and two shoulder straps. The seats in the two test series were structurally simple in order to minimize the number of test variables while assessing the model's capability of simulating large, plastic deformations. For each of those seats the seat pan and back consisted of relatively rigid frames, parallel and perpendicular to the floor. In the first series, the legs were fabricated from steel plate 76 mm wide and 6.35 mm thick, such that seat deformation would be confined to bending about a lateral axis and localized at the top and bottom of the legs. Two impact vector orientations were selected; the first orientation provided pure forward-facing ($-G_x$) acceleration. The second orientation provided combined longitudinal ($-G_x$) and vertical ($+G_z$) acceleration by reorienting the seat system so that the impact force vector fell 60 deg below the "floor" plane of the seat. Each configuration was tested at two levels of acceleration, nominally 9 and 17 G, with an impact velocity of about 13.4 m/sec. Tests were repeated until ten good data recordings were obtained for all measurements, so that the mean and standard deviation of the time history of the measurement could be computed.

The second series of tests were accomplished using a rigid seat with deformable tubular legs, 25-mm diameter and 2.2-mm wall thickness, replacing the plate sections, in order to evaluate the ability of the model to predict seat structural response in the presence of localized deformation changing the cross-sectional properties of critical structural elements. Fifty-eight dynamic tests were completed in the forward-facing ($-G_x$) orientations and with the floor angled at 60 deg to provide a downward and forward occupant reaction. Acceleration levels of 5.4 and 9.5 G provided minimal plastic deformation (without any significant cross section change) and marked plastic deformation (with localized buckling and cross section change at the fixed end), respectively, in the $-G_x$ orientation. In the tests with the floor angled, acceleration levels of 13.5 and 22 G were required to produce similar results.

These validation tests, which are described in detail in Ref. 18, indicated the desirability of several minor refinements in the seat structural model. After these modifications have been completed, a third series, using production aircraft seats of varying complexity will be conducted.

The response of the occupant model alone has been verified and improved using data from another series of dynamic tests conducted by CAMI as part of a comparison of three 50th-percentile dummy designs (19).

Because the only seats that have been designed to date according to well-defined crashworthiness criteria have been guided energy-absorbing seats, accurate simulation of such seats has been considered important. Using the energy-absorbing "rigid" seat option, a drop test of a UH-60A Black Hawk helicopter crewseat, described in Ref. 16, was simulated. The test configuration, as shown in Fig. 1, subjected the seat to combined downward, forward, and lateral loads, utilizing a peak deceleration of 48 G, a velocity change of 15.2 m/sec, and an approximately equilateral triangular deceleration pulse shape. The seat and mounting tracks were rotated in the drop cage through 30-deg nosedown pitch and 10-deg roll to achieve the desired load components. The test conditions were simulated using both two- and three-dimensional occupant models. For the two-dimensional case both the roll orientation and the lateral deceleration component were omitted.

Fig. 4 shows the occupant position, front and right side views, for a simulation of the Black Hawk crewseat test. At 65 msec the seat has stroked approximately

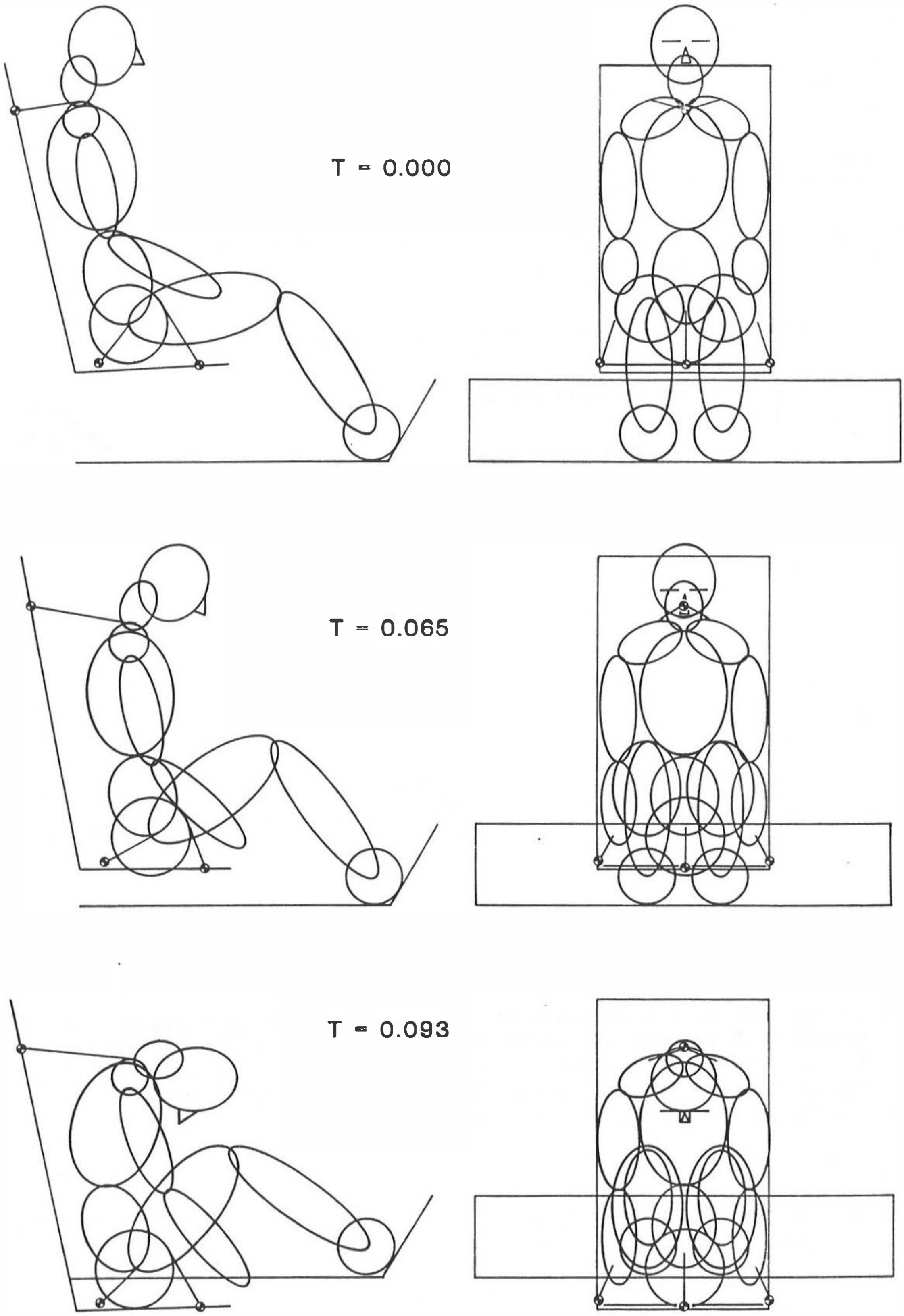

Fig. 4. Computer simulation of Black Hawk crewseat drop test.

12.7 cm below its initial position, and at 93 msec, approximately 35 cm, actually below the aircraft floor level. (The Black Hawk helicopter has a well in the floor below each crewseat to allow additional stroke.) Seat stroke predicted by the computer simulation is compared in Fig. 5 with that measured in the test. Acceleration data also compared quite favorably. The vertical component of the seat acceleration was of particular interest in the test because of its use in the seat criterion (MIL-S-58095) as an index of human tolerance. As shown in Fig. 6, the measured data showed peaks of 16, 24, and 33 G at 22, 34, and 90 msec, respectively. The predicted seat acceleration showed peaks of 16, 29, and 30 G at 22, 32, and 90 msec, respectively. The three-dimensional simulation produced occupant and seat displacements that were similar to the output of the two-dimensional model.

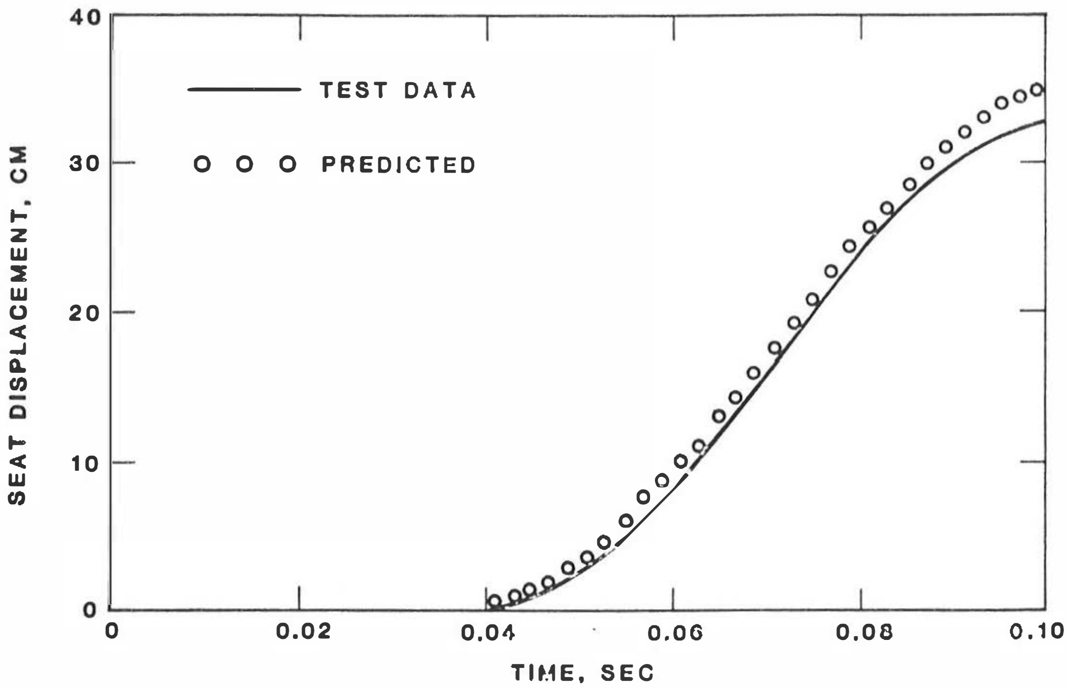

Fig. 5. Comparison of seat stroke measured in drop test of Black Hawk crewseat with computer prediction.

In order to aid in the development of more rigorous seat evaluation criteria, particularly with respect to spinal injury, a series of dynamic tests with human cadavers in a Black Hawk crewseat has been conducted. Comparison of the results of these tests with similar dummy tests indicated the need for significantly greater damping for simulation of a human subject.

Conclusions

A mathematical model of an aircraft seat and occupant has been developed for use in evaluation of the crashworthiness of aircraft seats and restraint systems. Program efficiency and ease of user input have been given considerable weight in development. Although further validation, based on testing of more complex seats and crash environments, is needed to establish the effective limits of the simulation, the procedure has the advantage of being independent of test data

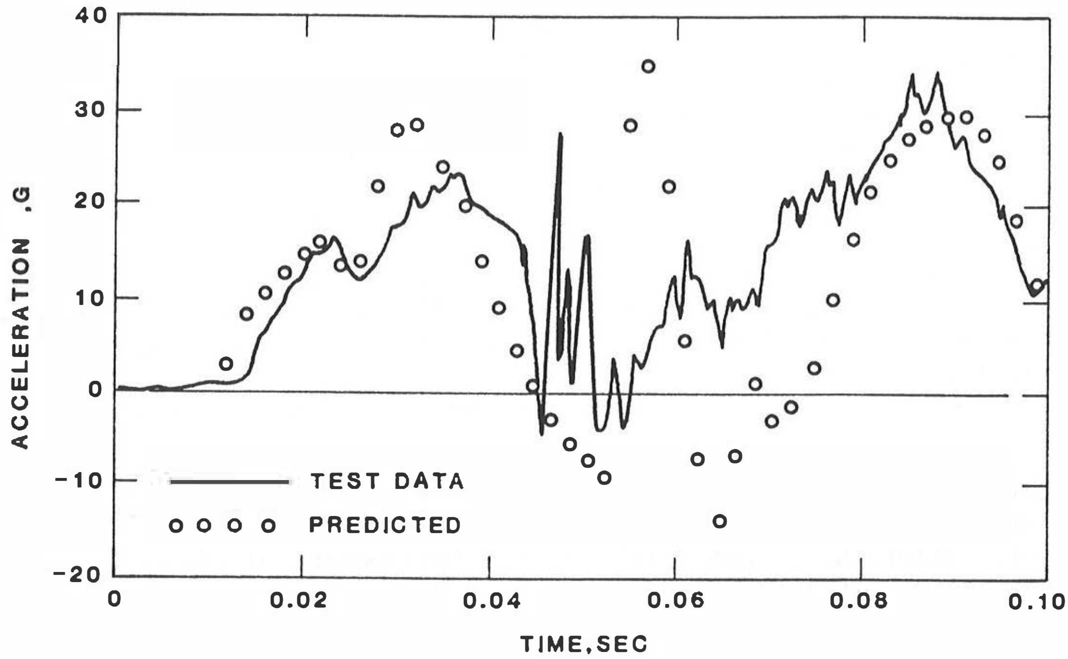

Fig. 6. Comparison of vertical component of seat pan acceleration measured in drop test of Black Hawk crewseat with computer prediction.

and requiring only information that is readily available to the designer. Satisfactory agreement of model predictions with test data has been demonstrated, and the model is considered to be a potentially valuable engineering tool for crashworthy design of aircraft.

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