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**KINEMATIC BEHAVIOR OF THE HUMAN BODY
DURING DECELERATION**

**J. J. SWEARINGEN, M.S., A. H. HASBROOK, R. G. SNYDER, Ph.D.,
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AVIATION MEDICAL SERVICE
AEROMEDICAL RESEARCH DIVISION
CIVIL AEROMEDICAL RESEARCH INSTITUTE
PROTECTION AND SURVIVAL BRANCH
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ABSTRACT

The geometry of motion of the head, trunk and appendages was established for one hundred male subjects restrained by a safety belt during forward and side dynamic loadings. Lethal structures of present aircraft seating and cockpit arrangements are revealed by correlating crash injuries with these kinematic data. In addition an analysis of the forces created by body kinematics during forward deceleration sheds new light on seat anchorage problems.

INTRODUCTION

For the past twenty years, dedicated research men have subjected themselves to deceleration tests, often suffering extreme discomforts and irreparable injuries in the process. Hundreds of animals have been sacrificed and millions of dollars spent in research to determine human tolerance to deceleration. Some scientists have concentrated their efforts in attempts to determine the forces necessary to fracture cadaver skulls, vertebrae, or other bony structures, or to investigate the forces and mechanisms of brain concussion. Others have searched for means of preventing injury by de-lethalization of structural components, or studied injuries and human tolerance in accidental falls and suicide leaps; still others have investigated body measurement relationships, and so on, infinitum. The monumental body of data resulting from these research programs — published in hundreds of scientific reports — consistently underlines one important fact concerning human impact survival; the human body can tolerate unbelievable g forces while

striking relatively large flat surfaces that can absorb energy by giving a few inches, but it is more fragile than china when impaled against narrow rigid tubes, protruding knobs, sharp edges and angles.

In order to obtain an appreciation of the average "habitat" of the *aircraft* occupant in small planes and transports, a study was initiated by the Protection and Survival Branch of the Federal Aviation Agency's Civil Aero-medical Research Institute.

It is the purpose of this paper to describe the results of this study by (1) presenting a detailed description of the areas which may be traversed by the human head, trunk, and appendages during flailing motions in crashes with safety belt restraint only, (2) relating present aircraft cockpit and seating arrangements with these areas of motion, (3) presenting an analysis of aircraft injuries, and finally (4) discussing some of the body impact forces which may be involved in a typical survivable transport crash.

FLAILING AREAS

To investigate the three-dimensional envelope within which the body is free to move during actual crash impacts, simulated tests were conducted, in which one hundred male subjects were accelerated forward and to the side over a two-inch safety belt by a weight-dropping mechanism. The orbits of motion of the body were recorded with reference to the midpoint of the line of intersection of the back cushion and *undepressed* seat cushion (which served as the reference point). The reference point was intentionally located on the undepressed seat to facilitate measurement to lethal structures while the seat was unoccupied. The results presented here are for subjects sitting on a cushion depressed two inches below the reference point before the test and 3 inches during the deceleration. These curves should be adjusted to the depression depth of other seat cushions which may be used.

Two suitable techniques were developed for recording the very rapid body motions whose duration was approximately 0.5 second. The photographic technique shown in Figure 1

utilized a crude focal plane shutter consisting of two opaque window blinds synchronized with the falling weights and with a camera time exposure of 0.5 second to photograph the subject's shadow on the screen. To eliminate the tediousness of reading shadowgrams from 4 by 5 inch negatives, a direct recording electrical contact technique was also developed (Fig. 2). The electrical contacts on the very light aluminum framework activated writing pens on a moving tape to record vertical and horizontal displacement of the subject.

Because of the low force (approximately 1.g) used to displace the body, the measurements presented here must be considered as minimal "strike" distances. In a crash situation, the greater forces involved—as well as the practice of passengers to wear their lap belts more loosely adjusted than the standard required for these tests—will permit larger magnitudes of body movement. It is interesting to note, at this point, that the tangential velocity of the head during these tests exceeded 12 ft./sec., as calculated from the horizontal and vertical accelerometers shown in Figure 2.

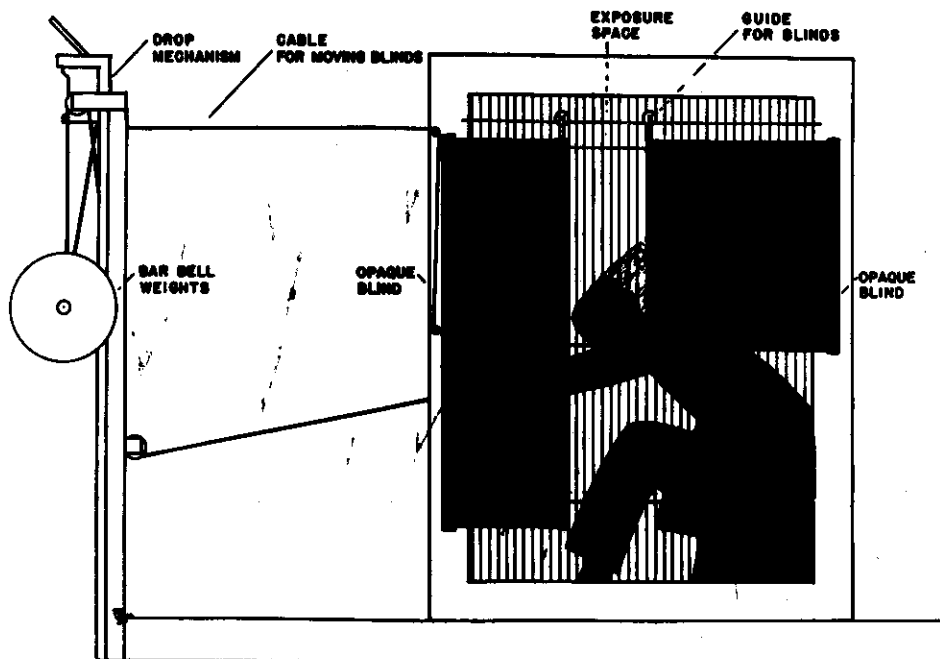


FIGURE 1.

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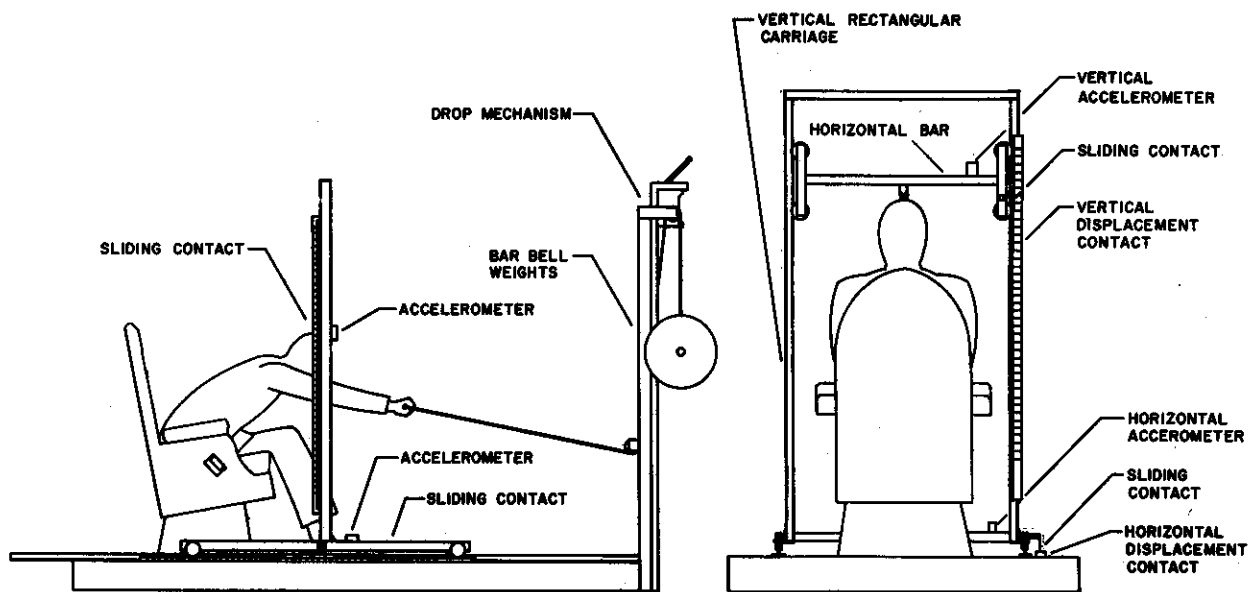


FIGURE 2.

Figures 3 and 4 present the 5th and 95th percentiles of the recorded paths of the tops of the heads as the subjects were accelerated forward and to the side over a *tight* safety belt. In addition, overhead arm reach (as taken from White⁵ and buttocks heel measurements from Snyder⁶) are superimposed with predicted paths of motion of the arms and legs during crash decelerations. These curves show that the flailing envelope for a single individual restrained by a seat belt is a sphere nearly 10 feet in diameter. Since it was found necessary to use body measurements from four different groups of subjects, Table I is presented to permit comparison of anthropometric sitting heights of these groups with the large Air Force sample measured by Randall.⁴

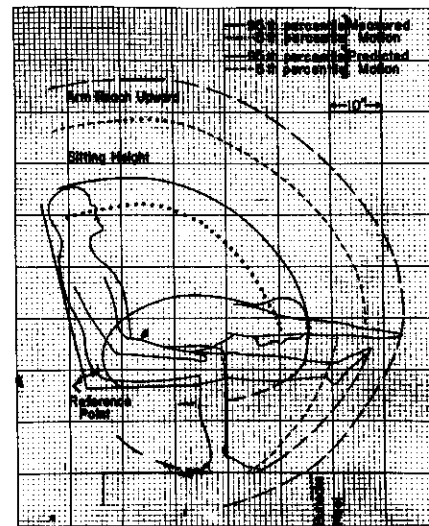


FIGURE 3.

TABLE I

Anthropometric Sitting Height		Randall ⁴	White ⁵	Snyder ⁶	FAA 100 in Fwd. Test	FAA 100 in Side Test
		5th	34.5	33.5	34.06	34.03
95th		38.5	37.7	38.22	38.37	38.41

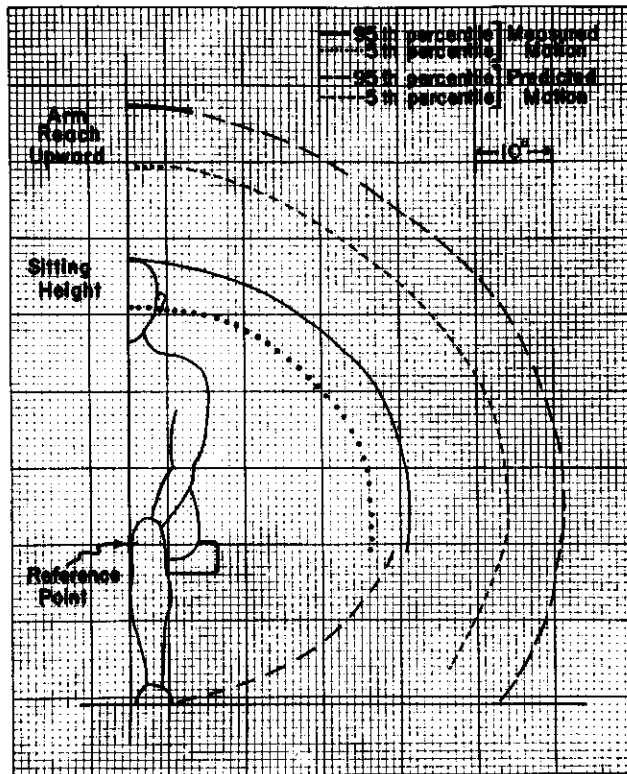


FIGURE 4.

BODY MOTIONS RELATED TO AIRCRAFT

To determine aircraft structures that are in the path of the flailing body, the 95th percentile curves of the subjects were superimposed on scale drawings of aircraft seating and cockpit arrangements. Since the head clearance curves were established with the safety belt adjusted as tightly as possible during the tests, delethali- zing the areas within the curves would provide protection for those persons in the upper per- centiles with tight belts, and would allow cer- tain degrees of freedom for those in the lower percentiles wearing the belt loosely adjusted.

Figure 5 shows the 95th percentile forward body clearance curves superimposed on a scale drawing conglomerate of a number of late model light aircraft. Since the head and torso are the usual sites of fatal lesion, the area with- in the head clearance curve may be considered the lethal area and the additional area swept over by the arms and legs might be classified as the "incapacitating" area.

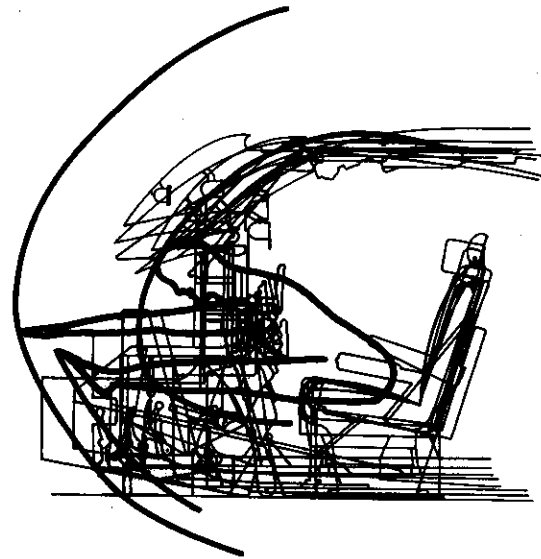


FIGURE 5. |

Figure 6 relates the lateral body clearance curves to a scale drawing of one of the largest personal type aircraft. Examination of Figures 5 and 6 discloses that almost all of the interior of the aircraft is within the lethal curve area.

The only body areas that are reasonably pro- tected from structure are within ten to twelve inches of the seat belt. Studying the statistics of injuries in survivable light plane accidents, it is not surprising to find that the number of injuries increases with increased distance from the seat belt. Figure 7 displays the pattern of injury of 800 survivors of light aircraft acci- dents, as reported by DeHaven¹; this appears to correlate well with the incidence of severe and fatal injury shown in the more recent study of 913 light plane accidents studied by Has- brook.² A large number of injuries to the head, upper trunk, and lower one-third of the extremi- ties is shown in DeHaven's study, as demon- strated in Figure 7. A number of fatalities oc- curred in this group of accidents, but data on

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injuries causing death were not presented because reliable autopsy data are rarely obtainable in instances where civilians are fatally injured. However, due to the large number of head and chest injuries among the survivors, death was probably associated most frequently with injuries to these body areas. This is substantiated by Marrow's report,³ in which head and chest injuries accounted for 337 of 342 fatalities.

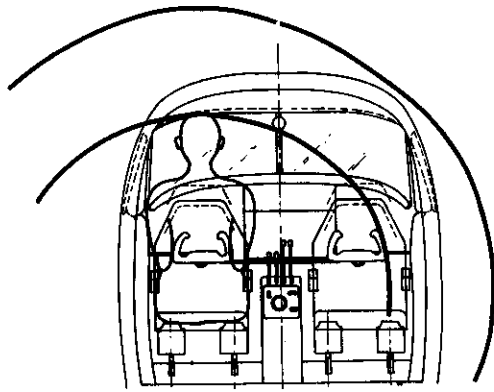


FIGURE 6. 2

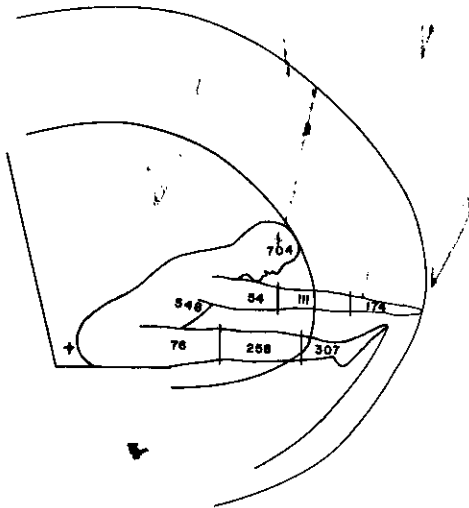


FIGURE 7.

The pattern of fatal and non-fatal injuries in commercial transport crashes closely parallels that presented herein for the private pilot. There is one notable post-crash difference; unconscious and incapacitated passengers in commercial transport accidents are often trapped and die in the smoke, fumes and fire that follow the crash—light aircraft seldom burn.

When the flailing curves are applied to present day commercial transport seating arrangements (Fig. 8, 9, 10), it becomes obvious that, because of the overlap of body movements and the extensive arc necessary to protect even one individual, almost every square inch in the cabin is covered by the combined body movements of all the passengers; therefore, all rigid objects and structures within the cabin may be considered as having a lethal potential. Since the sphere in which an individual should be protected from injury is nearly 10 feet in diameter, it would be necessary to limit even our largest jet transports to one row of seats down the middle, spaced five feet apart, in order to offer adequate protection *without* delethalization. Such spacing is obviously impractical. Therefore, efforts to increase crash survival must be aimed at (a) delethalization to maintain impact forces below human tolerance levels and (b) improved seat anchorages to insure that seats remain in place until the cabin disintegrates.

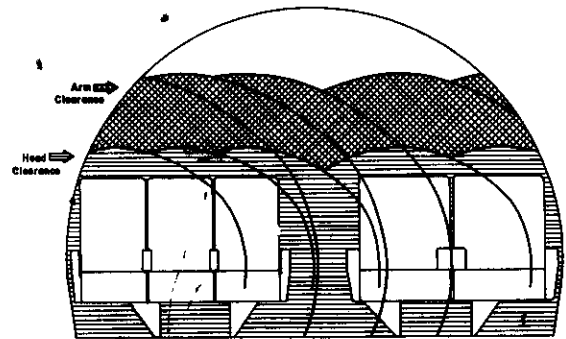


FIGURE 8. 3

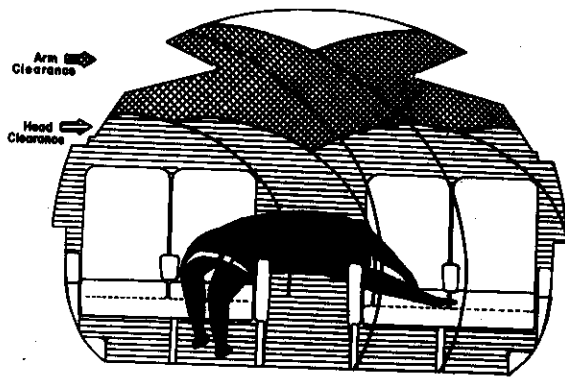


FIGURE 9.

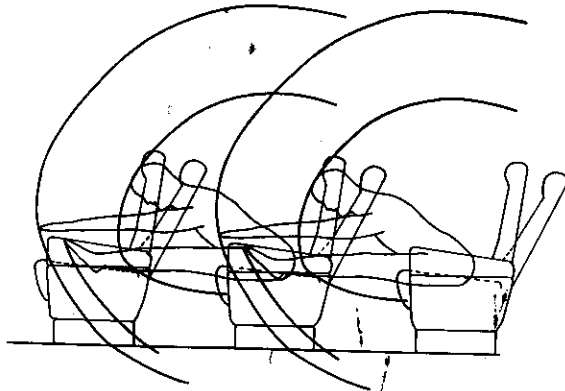


FIGURE 10.

FORCES OF BODY IMPACT

In studying the range of possible body movement in transport seating environments during crash decelerations, it becomes obvious that a passenger restrained only by a seat belt in a forward facing seat will strike the seat directly ahead. Impact of head, upper torso, arms and legs against a seat must result in some force

being imposed on that seat. If the "strike" loads imposed by the occupant on the seat ahead are of high magnitude, it is possible that these forces may be responsible for seat-anchor-age-floor failure in accidents in which the aircraft deceleration imposes loads that are well below design load requirements. Current design requirements are based on tests which consider only the weight of the seats and occupants. This may explain to some degree why seat tie-down failure has been observed to occur in apparently haphazard patterns in some survivable transport accidents. It may also provide an answer to why the rear-most row of occupied seats sometimes remains secured to the floor while the occupied seats ahead break free—such as occurred in a Convair 240 accident at Springfield, Missouri, and in the Boston and LaGuardia Electra accidents. Hence, it would seem desirable to determine the magnitude of these body impacts.

An evaluation was made of the possible effects of body strike loads, in a hypothetical crash landing condition, in which the operational flight parameters, as well as the decelerations acting on the aircraft were considered to be within realistic proportions—as related to current turbo-jet transport operation.

The crash landing condition chosen assumes an early "flare out" in which the aircraft's rate of descent increases rapidly, resulting in failure of the landing gear and application of reasonably "heavy" crash loads to the belly structure. The aircraft, with a horizontal impact velocity of 172 ft./sec., decelerating to 106 ft./sec., in about 24 feet in .17 second, would experience a 12 g horizontal deceleration; assuming a 33 ft./sec. vertical velocity and 2.8 feet crumpling of the belly structure during the same interval, the aircraft would sustain a 6 g vertical deceleration.

Evidence indicates that these decelerations (12 g horizontal and 6 g vertical) are representative of the worst conditions which most of the latest domestic passenger seats can be expected to resist without failure.

Figure 11 shows that the loads which could be applied to seat No. 1 by its occupants were computed to be 3,708 pounds horizontal force, 6,448 pounds compression on the front legs of the seat and 4,600 pounds tension on the rear leg attachments. These computations *exclude*

the weight of the seat itself, due to lack of readily available, precise data on weights and centers of gravity of passenger seats of current design.

Assuming that the head and lower leg can deliver blows equal to 200-300 g, the floor loads experienced under seat No. 1 increased appreciably as a result of the impact of the heads and legs of the occupants of seat No. 2, as indicated by the reactions shown parenthetically in Figure 11.

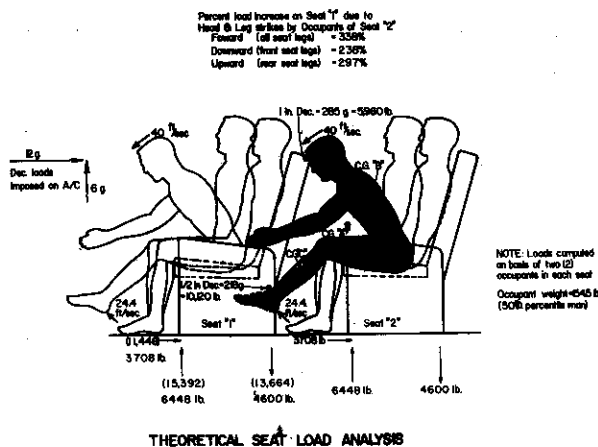


FIGURE 11.

For example, the total vertical tension load on the two back legs of seat No. 1 was increased from 4,600 to 13,664 pounds by the impacts of the occupants in seat No. 2. In other words, over two-thirds of the total force acting to pull the back legs of the seat out of the floor is imposed on the seat by the passengers in the next seat behind; yet in present day seat testing, only the loads imposed by the seat and its occupants are considered. Thus, a so-called 12 g seat is probably not good for more than 3 g (horizontally) under the conditions cited above.

The deceleration factors of 285 g for the head and 218 g for the legs are based on a 1-inch deceleration distance during head-seat-back impact, and ½-inch deceleration distance for the legs against the rigid lower cross member in the basic seat frame. While it is known from studies of individuals falling from high buildings that the human head and legs can, (if properly supported), sustain such high decelerations without fracture, one would expect that forces less than those demonstrated here theoretically would result in fractures of these body parts due to striking the rigid tubular structures of present day seats. Preliminary results of a current study being conducted in our laboratories to determine the fracture forces of the lower leg during dynamic load application indicate that the tibia fails at approximately 100 g when impacted against a cylindrical structure one inch in diameter. Since the weight of the lower leg and shoe varies from 7 pounds, for a 100-pound woman, to 15 pounds for a 200-pound man, each leg can be expected to exert an impact force of between 700 and 1,400 pounds for a total of between 2,800 and 5,600 pounds for four legs.

Delethalization, based only on spreading head and leg impact loads over larger areas—without use of energy dissipating materials or devices—will substantially increase these loads on the seat due to prevention of leg fracture at the above mentioned loads.

In any event, as shown here, a seat designed to resist horizontal and vertical decelerations of 12 g and 6 g respectively could be severely overloaded by as much as an average of 291 per cent when struck by the occupants of the seat directly behind, in the crash landing conditions cited above. This would indicate, therefore, that currently accepted testing procedures—as well as seat design parameters—do not provide a realistic approach to crash-worthy seat design, and that consideration should be given to these "strike" loads imposed on the rear of the seat.

SUMMARY

The study of motion of a human body restrained only by a safety belt is presented and is briefly described as the area within the upper two-thirds of a sphere 10 feet in diameter.

Application of body clearance curves—developed in the study—to present aircraft seating arrangements shows that the entire interior of most aircraft—large or small—can be reached by one or more parts of the flailing body.

It is suggested that there is needless injury and loss of life from impact with rigid structures in cabin/cockpit environments and in current seats, which can be eliminated by improved seat design incorporating delethalization, especially in seat arms, seat-backs, and rigid structures in and under the seat-back.

Current seat tie-down requirements are inadequate, especially in the vertical direction; the 2 g (upward) requirement, based only on the weight of the seat and its occupants, gives a vertical tie-down strength of something under 1,000 pounds. It is shown in this report that the lifting force of the four legs of the passengers seated behind the seat in question may be expected to exceed this tie-down strength by a factor of 2 to 5 before fracturing. In dynamic seat testing, consideration should be given to strike loads imposed on the rear of the seats.

In considering leg strike loads, the practice of storing brief cases and small suit cases under the seat should be viewed with suspicion, since these objects can slide forward against the backs of the passenger's legs, increasing the force of leg impact against the seat, and possibly entrapping the feet under the seat.

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