AM 65-12

SURVIVAL OF HIGH-VELOCITY FREE-FALLS IN WATER

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April 1965

FEDERAL AVIATION AGENCY
Office of Aviation Medicine
Civil Aeromedical Research Institute
Oklahoma City, Oklahoma

ACKNOWLEDGMENTS

The author gratefully wishes to acknowledge the generous assistance provided in this study by Joseph W. Young, A.M., and Clyde Snow, M.S., Physical Anthropology Laboratory, CARI; John C. Earley, Chief, Dynamics Engineering Laboratory, CARI; Robert Dille, M.D., Regional Flight Surgeon, Western Region, FAA; Jim Scow, M.D., Langley Research Center, National Aeronautics and Space Administration; John Ice, Technical Editor, Acceleration Program, CARI; Laura Newell, Ph.D., Dept. of Anthropology, University of Washington; and Capt. T. F. Parnow, California Highway Patrol. In addition, this study would not have been possible without the extensive cooperation and assistance provided by individual physicians, federal, state, and local police agencies, witnesses, and the subjects themselves.

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I. Introduction.

Protection and survival of the aviation population involves many interrelated facets of varying interest to the design engineer, human-factors specialist, and aeromedical scientist. Progress in most of these areas eventually is dependent upon basic knowledge of human capabilities and tolerances to the varied, and often hostile, environments imposed by flight. One such area is that of human tolerances to impact forces, in which considerable work has been done involving the horizontal component at subinjurious levels. Relatively little is known, however, concerning human-tissue responses to vertical forces, partially at the higher sublethal levels.

High vertical forces are most often encountered during crash landings,[1, 2] evaculation from the aircraft after it has stopped,[3, 4] or during extreme turbulence in flight. [5, 6, 7] Such forces are often unintentionally encountered by parachutists who are unfortunate enough to be dependent upon ailing equipment. They may also be anticipated in VTOL-type-aircraft launch and landing accidents.

Quite often the material impacted in high-velocity vertical impact consists of a water surface; thus, both the general incidence and peculiar characteristics of water survival merit study in greater detail. One immediate application for such knowledge is in the impact survival of astronauts exposed to extremely abrupt decelerations upon water impact due to retro-braking equipment failure. In re-entry a drogue failure may result in a splash-down of 130 ft/sec (88.6 mph) or more. Impacts in water of 25,000 G/sec, with a peak of 60 G, [8, 9] or 100 G land impacts[10] for the Mercury capsule have been predicted. In this regard it is imperative to know the design limitations of the human body to such forces before a judgment can be made as to "how great an impact is survivable." This is far from a simple question to answer and dependent upon a number of interrelated and variable conditions. This study is one attempt to initially define some of these variables and find means of predicting human survival in water impact.

Human falls into water from great heights have been recorded throughout history. These have not always been successful, and perhaps the mythical fall of Icarus into the sea as he attempted to escape from Crete with his father, Daedalus, was the first. Although early medical references, such as Gould and Pyle's Anomalies and Curiosities of Medicine of 1901,[11] provide several cases of "Remarkable falls" into water, including that of a sailor who survived a fall of 120 feet from the topgallant of an East India merchant vessel, early falls do not compare with the much greater heights man commonly falls from today. Man himself has provided the means in constructing tall bridges, towers, aircraft, and other suitable structures from which he daily jumps, falls, or is pushed. These incidents may provide valid scientific information that is unobtainable through laboratory experimentation because of the obvious limits human voluntary subjects can be exposed to in impact. On the other hand, free-fall cases may present involuntary experiments in which the subject greatly exceeds these laboratory limits. In selected cases, in which investigation results in documentation of the major variables, certain conclusions are valid. As this study progresses and sufficient cases occur to reproduce and reinforce the evidence to date, definite patterns of trauma should become evident, as well as discrete indications of the major variables influencing human survival of extreme impact forces.

There is apparently a wide, overlapping, and variable area between human limits of minimal injury as found in the laboratory and the extreme limits of survival. Although this has been explored to date to only a limited extent, knowledge of the variables and problems involved should be of considerable application to increased protection and survival of the individual involved in abrupt deceleration occurences.

II. Materials and Method.

During the past 3 years, cases have been carefully documented of voluntary and involuntary free-fall ,with particular emphasis upon survival.[12, 13, 14, 15] Of some 18,000 cases during this time involving survived free-falls, and 7,000 fatal incidents of which we have knowledge, 200 survived cases to date have been selected for more intensive investigation. Forty-four cases of human impaction with water surfaces in unimpeded free-falls of 55 feet (velocity of 52 ft/sec, or 35.5 mph), or higher, are included. In each case, a site investigation was made, actual measurement made of the distance of the fall, interviews conducted with the subject and witnesses, photographs and police reports obtained, and the complete medical history forwarded, including copies of any x-rays. From these data, calculations of free-fall velocity and direction of forces were obtained from analysis of the medical and biophysical evidence.

This population represents a highly select group of individuals in that they had to have survived an extreme impact of over 50 ft/sec on a water surface. Additionally, except for four cases occurring prior to 1962, they represent a high proportion (96%) of all known survivals under these specific conditions during the past 3 years. It must be emphasized that the total population that fell under these conditions is not considered here since fatal cases are not included. Therefore, the actual incidence of survival is not shown but rather a discrete analysis of the micropopulation that did survive. The following data must be used with this limitation in mind.

III. Results.

The 44 falls investigated occurred in 17 different states (Figure 1) with 9 in Washington, 7 in Massachusetts, and 5 each in California and New York. All but 4 cases involved falls from bridges, with 24 of these being suicide attempts (Figure 2).

Bridge construction and painting accounts for a high incidence of falls from great heights into water. Towers of the Golden Gate Bridge, for example, jut 746 feet over the San Francisco Bay, while the towers of the New Verrazano-Narrows Bridge between Staten Island and Brooklyn are 690 feet over New York Harbor, and other bridges (Glen Canyon Dam Bridge) are even higher, providing constant exposure to the hazards of free-falls for such workers. (Although two cases of parachute failures were obtained, including one involving an ejection from 15,000 feet over the Pacific Ocean and a second, a female sky-diver falling 2,550 feet into a pond, these are not included here since aerodynamic drag could not be accurately determined in either case.) In each case, measurement of the distance of the fall allowed calculation of the velocity. Note that standard velocity in each case has been corrected for air drag at sea level (standard pressure, assumed body terminal velocity of 120 mph).

The calculated values used in this study are thus lower, but more realistic than that provided by the standard formula ($V = \sqrt{2gS}$) alone, since preliminary tests and mathematical calculations have shown that clothing such as jackets or skirts do provide additional drag. Corrections by Earley[16] are based upon Cotner's[17] closed-form solution for velocity at impact for fall cases where body position and clothing was observed to be constant. A mean body build of 4.7 C_DS (drag coefficient × body surface area) was utilized.

In Figure 3, velocity is plotted against the variables of age, sex, and body orientation (direction of force) at impact. There were 34 males and 10 females in this study. Although age extremes of 7 to 80 years were involved, 69% of the subjects were between ages 20 and 40, and all of those surviving impacts greater than 100 ft/sec were between 7 and 26 years of age. Seven, or 70%, of the females surviving these extreme impacts were between ages 20 and 29. There is thus some correlation with age, with a greater number of younger individuals, both male and female, having survived at the higher impact velocities. This probably reflects physical condition to some extent, although a subjective assessment was not available; however, this does not present the total incidence of survival, which would show whether this could be due to greater exposure at higher velocities.

Survival occurred in various body positions up to 87 ft/sec lateral ($-G_y$), 88 ft/sec prone ($-G_X$), 93 ft/sec supine ($+G_X$), and 97 ft/sec head-first ($-G_Z$). At all levels of velocity (distance of fall from 46 feet) above 50 ft/sec, however, the feet-first ($+G_z$) impacts had a *significantly* higher survival incidence. Aside from the two parachute failures, which are assumed to be terminal-velocity impacts, four other cases of survival occurred in the feet-first body orientation [at 100, 102, 111, and 116 ft/sec (133 ft/sec standard velocity)].

The upper survival limits of human tolerance to impact velocity in water are evidently close to 100 ft/sec (68.2 mph) corrected velocity, or the equivalent of a 186-foot free-fall. As is illustrated in Figure 3, there is a fairly constant survival frequency distribution up to 100 ft/sec, but survival incidence at higher levels drops off abruptly and includes younger individuals only. Regrouping these cases of survival by arbitrary class intervals, as in Figure 4, shows this pattern with an abrupt peak at a 100-ft/sec impact velocity. Twenty-five percent of these individuals survived extreme impact in water at from 90 to 100 ft/sec, while only 4.9% survived a greater impact at any level.

Previous studies involving human impacts on other surfaces, such as concrete, steel, and soil, have demonstrated no clear-cut correlation between the distance of fall (and impact velocity) and degree of resulting trauma. The 44 cases of water impact studied in this investigation also show no correlation of velocity (distance) with injury. In one case, for example, serious injuries occurred from a 55-foot free-fall (velocity 58 ft/sec, or 39.5 mph), while in others of much higher velocity, minimal contusions or no injuries were reported. No clinical injuries were reported in one case at 95 ft/sec (64.8 mph) impact and another 178-foot feet-first fall impacting at 97-ft/sec (or 66.1 mph) velocity.

Patterns of injury were found to vary with the direction of force or body orientation. This is shown in Figure 5, in which gross injuries were summed up into four arbitrary classifications—no injury, external tissue injury, skeletal injury, and injury to internal organs, tissues, and systems. Of 34 cases of feet-first ($+G_z$) impact, which was the most commonly survived body orientation, 11, or 32.3%, had no associated trauma clinically reported. In all other body orientations, some injury occurred. The most typical injury in feet-first impact involved contusions to thighs and buttocks, compression fractures (particularly to the twelfth thoracic and first lumbar vertebra), shock, and hemorrhaging of the lung.

Besides the high incidence of compression fractures in this impact position bilateral midshaft fractures to the tibia and fibia, femur, or humerus occurred. In one case, a comminuted fracture of the scapula and distal clavicle occurred when the individual landed with one arm down, forming a fulcrum against the impact force. Fracture patterns in water are distinctly different from those that occur on concrete, steel, or soil surfaces since not one case of foot or ankle injury was reported for the former, while in the latter a high frequency of fractured ankles in feet-first impacts has been found. The midshaft fractures also differ from the pattern most typical of impacting nonwater surfaces. This probably occurs as a function of pressure changes as the body angles into the water, literally snapping the long bones unless the legs are kept together. Extensive internal trauma occurred in only five individuals (14.4%), but the lung, kidney, spleen, liver and bladder appeared most susceptible to injury. One case, although fatal 48 hours later, showed upon autopsy a ruptured liver, spleen, and intercostal artery. Often internal trauma of a more minor nature, such as tearing of organ membranes, may remain undiagnosed, as is indicated by numerous autopies in our files. Other studies of human water impacts have also confirmed the high incidence of external skin lesions,[18] and noted the extensive injury to internal organs in survivable impact. [19, 20, 21, 22]

Impacts in the five other positions identified are reported but, since only one to three occurences were obtained for each, the results must be interpreted with caution. It does appear that internal trauma is significantly more frequent in any position of impact other than feet-first. Only 1 (head-first) out of 10 cases of impact in another position failed to result in internal injury, with renal hematoma being most common. Two individuals striking buttocks first, one at near terminal velocity, were both injured, receiving similar injuries as those impacting feet-first, except for one who landed on his buttocks and right side, thus receiving a fractured second lumbar vertebra transverse process and fracture of 10 ribs.

Other data were secured in investigation of each case, such as clothing worn, physical data, meteorological conditions (depth of water, wind, current, and tide conditions), and whether the subject had been intoxicated, under the sedation of drugs, or had a psychiatric history. In three cases, jump boots and other protective clothing such as helmets, a water skier's float, or heavy clothing may have contributed to preventing further injuries. Several individuals, however, carefully shed clothing prior to jumping. Although it is felt that knowledge of the possible influence of drugs, alcohol, or certain psychiatric conditions would be useful for comparisons in their relationship to impact survival, the clinical data are not specific enough for a valid comparison. Although 14 individuals were noted to be alcoholics, intoxicated, or to have been drinking prior to impact, in no case was a blood-alcohol determination made that would allow more objective comparison with presumably sober jumpers. In addition, 15 individuals, including some of the intoxicated ones, were also diagnosed to have various mental abnormalities, the most common of which was schizophrenia. Although previous work[13] has suggested a relationship between relaxed muscle tonus, as may occur in the intoxicated individual, and impact survival, the data obtained to date in water impacts are not felt to be adequate for inclusion.

IV. Discussion.

While it has generally been considered that the wider the distribution of force over the body's surface, the less the unit force, and thus the greater distribution of energy (and survival capability), this one factor by itself is somewhat misleading, particularly in regard to water impact. For example, practically everyone has experienced the "belly flopper," which is a distribution of force over a wide surface area. Yet a clean dive or jump into water, representing a much smaller surface area and thus greater concentration of force, leaves little or no sting. The difference, of course, is in the deformation characteristics of the water, and thus the distance and time duration of deceleration. In the "belly flopper," the time duration of impact is short, and "braking action" due to the greater surface area results in shorter stopping distance, while in the clean dive the time duration of impact is greater since there is less braking action due to decreased body surface area and greater depth penetration. While this may seem obvious and elementary, it is a basic factor in water-impact survival.

Velocity at impact is used in this study to indicate magnitude of force because it can be accurately calculated in unimpeded free-falls, providing a valid basis of relative fall severity. Unlike falls onto hard surfaces such as concrete, however, the deformation characteristics of each impact cannot be precisely determined since the displacement is not known. Thus, time duration, a most important factor in deceleration calculations, cannnot be accurately determined. In general, the time duration, and rate of change of velocity, in water impacts is of much longer duration than in impacts on solid surfaces.

Stopping distance will vary with the body orientation at impact, being much greater in feet- or head-first impacts, and less, because of the greater surface area, in lateral or transverse impacts. Evidence does seem to indicate, however, that even from great heights velocity is rapidly lost in water.[23, 24, 25] Experiments by Neuriter and Trey, for example, showed that in head-first dives into water from 238 cm (7′9″) dummies (mass 3.38 kg, specific gravity 1.08) had lost 71% of their velocity by a depth of only[16] 16 cm (6.3″).[26]

We intend to conduct further experiments and try to duplicate with instrumented subjects specific conditions of free-fall in order to caluate time duration sand estimate G forces acting upon the body. Preliminary calculations involving stagnation theory indicate that G forces upon the body in water impact are five to seven times greater in the prone ($+G_X$), supine ($-G_X$), or lateral ($\pm G_y$) body orientation than head-first ($-G_Z$) or feet-first ($+G_Z$) impacts. Mathematical estimates by Earley[17] predict a magnitude of force in feet or head-first impacts of approximately 3.5 G at 20 ft/sec, compared to 18.6 G in a flat configuration, 6.0 G versus 40 G at 30 ft/sec, 16 G compared to 112 G at 50 ft/sec, and 43 G compared to 300 G at 80 ft/sec. If correct, these approximate theoretical values suggest a major reason why incidence of water-impact survival is so much greater in head- or feet-first configurations. For the same distance of fall and same velocity, an individual may thus protect himself by roughly 50% to 70% from G forces acting on the body by presenting a minimal surface area at impaction.

It should also be noted that while plots of these theoretical values provide two divergent lines, in most cases (except for trained professional divers), the minimum line will show several peaks after initial impact and may even rapidly approach the secondary maximum levels due to change of body orientation after initial impact.

In water impacts, factors not usually associated with ther types of surfaces may play an important role in determining survival. For example, the surface of the water may be smooth and horizontal to the falling body or through waves and throughs form a surface angle nearly perpendicular and thus parallel to the body. Even in inland waters, waves may be a factor. Velocity of the current, while a relatively minor factor at impact, is immediately important to survival. Meteorological conditions thus are often of more importance to water impacts than other impacted surfaces less subject to variation. Additional forces acting in a water impact may involve such factors as friction, tumbling, water upslope, resultant forces, and even shear due to current.

While most bridge-jumpers are attempting to commit suicide, and others fall accidentally, it should be noted that there are two further groups of voluntary jumpers, both gamblers in a sense. The first of these are those, usually young males, who jump on a bet. Strangely enough, we have only one case of a known "bettor" who has been killed. But frustratingly enough, there are seldom records of such cases, and the individuals usually, presumably clutching their winnings, elude official searchers. In recent cases of this nature, a Rhode Island youth leaped 60 feet from a bridge while his companion stood by yelling encouragement, and another jumped 135 feet and was last seen swimming to a pier. In Ohio, a 17-year-old boy jumped 65 feet, and in New York a 32-year-old man jumped 107-feet—for the third time—from a bridge on which 67 other jumpers have been killed.

There have also been several men who make a somewhat precarious living as stunt-jumpers, and their techniques may provide useful information. In 1961, the present unofficial world record for a still-water dive was made by one such individual diving 109 feet 7 inches into the Sea Circus pool at Pacific Ocean Park, Santa Monica—the equivalent of an 11-story jump. This same individual has jumped 155 feet into moving water. Perhaps the champion voluntary jumper was Ray Woods, who jumped all over the place in the mid-thirties, jumping 165 feet from the Aurora Bridge in Seattle in 1935 and surviving, with back injuries that ended his carreer, a fantastic dive of 186 feet from the San Francisco-Oakland Bay Bridge in 1937. A third diver, during opening ceremonies of the Mt. Hope Bridge at Portsmouth, Rhode Island, in 1927, jumped 154 feet, wearing a padded suit and helmet.

In various parts of the world other high divers frequently dive great distances. In Mexico, for example, professionals regularly dive distances of 100 and 135 feet from a Pacific Ocean cliff at Acapulco, Mexico. One of these has dived this distance approximately 26,000 time in 25 years of diving. A study by Schneider, Papo, and Alverez [27] notes that no fatalities have occurred, except to an American college diver who attempted to duplicate this feat. Various injuries have been incurred, however, including fractures of the metacarpals or radius and ulna, caused by the extremities striking the head on impact with the water. Compression fractures were found in four of six divers examined, involving the fifth thoracic vertebra in three cases, the sixth thoracic vertebra in two cases, and the second, third, fourth, and seventh thoracic vertebra. Along with well-developed neck muscles, their success is attributed to either extending the arms or locking the fingers so as to "strike so that their necks are slightly hyperextended and the point of impact is at the bregma." [27] In the "hands-apart" impact the force was mainly taken on the head, while with the hands locked cavitation resulted in less force on the head.

The leader of this group of divers noted that in diving from less than 30 feet a diver should remain relaxed; over 30 feet he "must be as rigid as possible to take up the blow."[27] Such stunt dives do emphasize that a water impact can be repeatedly made at velocities up to 86 ft/sec with no or minimal injury if proper body orientation is maintained. These individuals, however, are all young males, highly trained, and in top physical condition.

Previous experimental water impacts with anesthetized guinea pigs, in an attempt to reproduce trauma in free-fall of the two 1954 Comet Airline ruptures that spilled occupants into the sea, resulted in the conclusion that severe internal injuries may be expected in extreme water impact and that the critical velocity for guinea pigs was about 104 ft/sec.[28] Critical incident velocities for the mouse (118 ft/sec), guinea pig (99 ft/sec), and man (94 ft/sec) were predicted in a separate study.[29] Both of these previous theoretical and animal impact studies are in general agreement with the findings of these human free-falls in water.

The etiology of these falls, particularly in cases involving mental disorder, alcohol or drugs, may be of importance in evaluating each case of survival. As note previously, however, discrete data as provided by most clinical histories do not provide objective enough data in these water impacts to more than suggest a relationship. Many more intoxicated schizophrenics, for example, may survive extreme water impacts, but this cannot be scientifically interpreted without knowledge of the total incidence—do proportionately more intoxicated schizophrenics jump—and are proportionately more thus also fatally injured? These are questions to be investigated in subsequent analysis of our fatal cases and, particularly, of the autopsy cases.

V. Summary.

Forty-four cases of free-falls survived by individuals impacting water environments under conditions of high velocity (50 to 176 ft/sec) have been intensively investigated and analyzed. Ages varied from 7 to 80 years and the study included 34 males and 10 females. The falls occurred in 17 different states primarily over a 3-year period, and included attempted suicides, accidental falls from high structures, and parachute failures in jumping or evacuating from aircraft.

It was found that:

A. The most survivable body orientation, by a factor of five to seven, is in a feet-first ($+G_z$) impact with arms over the head, due to increased time duration of deceleration caused by minimal body-surface-area braking action.

B. Critical velocity for human survival of water impact in the feet-first body position appears to be at about 100 ft/sec. Four cases ranged from 100 to 116 ft/sec, and in two cases terminal velocity was approached. The highest impact velocity survived was 87 ft/sec, in the lateral ($-G_y$) body orientation, 88 ft/sec in the prone ($-G_x$) position, 93 ft/sec supine ($+G_x$), and 97 ft/sec head-first ($-G_z$). (Note that velocity calculations were corrected for aerodynamic drag and thus are lower than standard values.)

C. No correlation between velocity (or distance of fall)and degree of trauma was found; rather, injuries appeared to be more dependent upon body position at all levels of force. Severe injuries (and fatalities)occurred at low levels of velocity, while some cases of minimal or no injury occurred at very high-impact velocities.

D. The pattern of impact injuries in the feet-and buttocks-first position showed a high incidence (68%) of fractures, with compression fractures to the first lumbar and twelfth thoracic vertebrae the most common single injury. Bilateral midshaft fractures were also typical in cases of fracture. Only 14% received internal trauma, with lung hemorrhaging being most frequent. Sixty-eight percent also received a distinctive pattern of contusions involving primarily the thigh and buttocks area. Eleven individuals of thirty-four (33%) received no clinical trauma in feet-first impacts. Contrary to impact findings on solid surfaces, no injuries to the feet or ankles occurred.

E. In lateral and transverse (prone and spine) impacts in water, all individuals received injuries with 100% incidence of internal trauma (with renal hematoma most prevalent single injury)and 100% body contusions. Rib and basalar skull fractures occurred in both lateral impacts, and compression fracture of the first lumbar and twelfth thoracic vertebrae occurred in the supine position, with no fractures in the one prone impact.

F. There was a distinct correlation of age with survival as the level of velocity was increased, with both sexes showing higher impacts survived at ages 20 to 36; however, since fatal cases were not included, this could also reflect a higher exposure rate.

G. Sex did not appear to a factor in survival.

H. Other factors considered to be of varying influence on water-impact survival included wind direction and velocity, water condition and current, protective clothing, physical condition, mental condition, and influence of alcohol or drugs.

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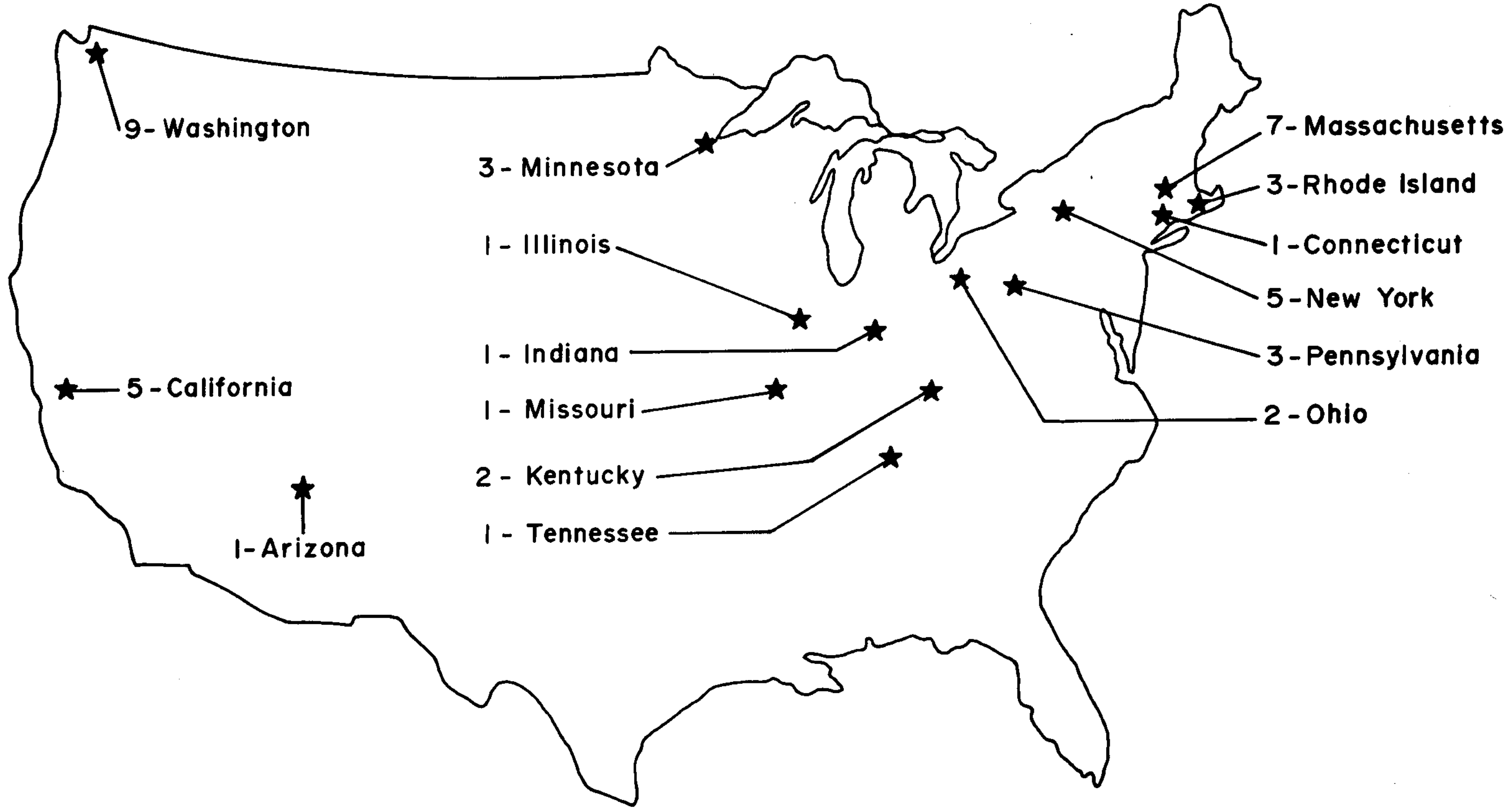

FIGURE 1. Geographic Distribution of 44 Survived Free-falls Over 47 Feet Into Water.

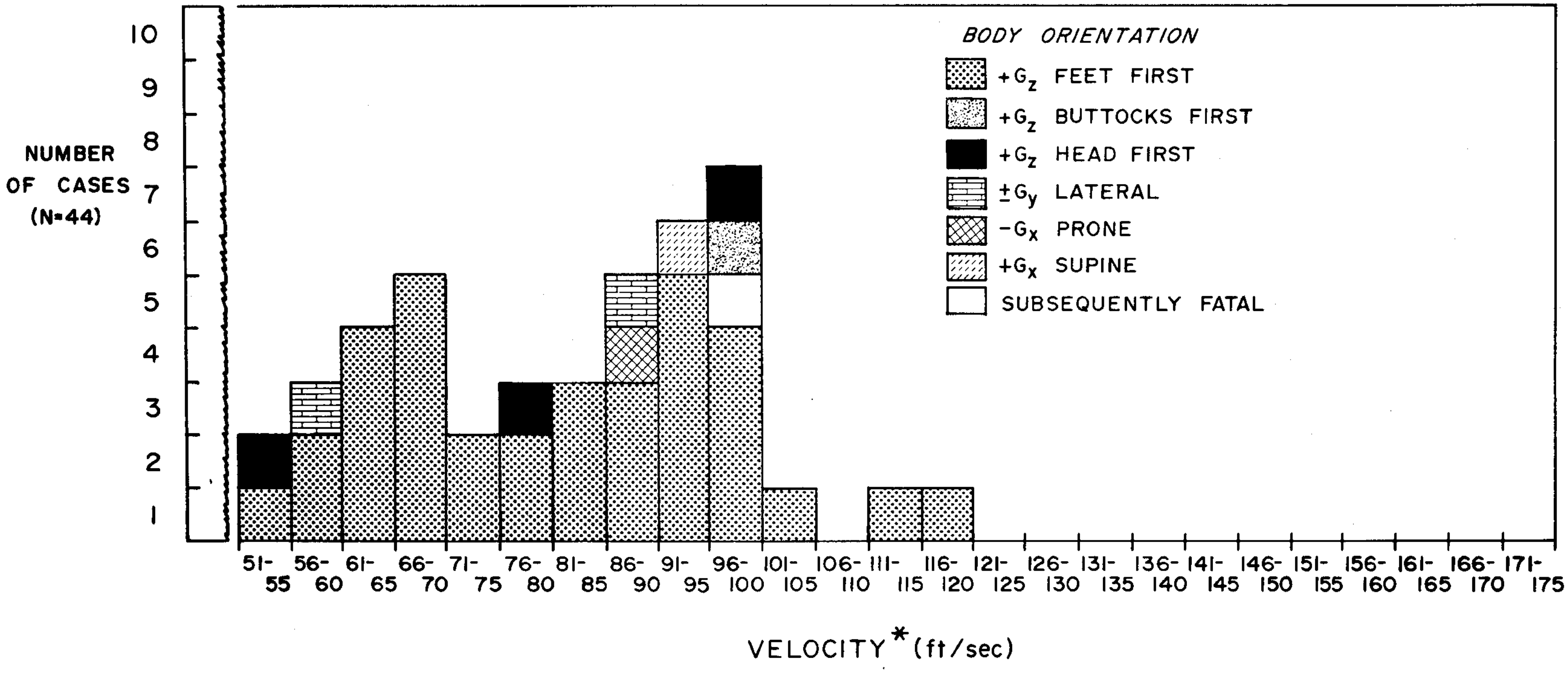

FIGURE 4. Incidence of Human Water-Impact Survival From Velocities Exceeding 50 ft/sec (Velocity Corrected for C_D).

Direction of Force	None	External Tissue	Skeletal	Internal Organs, Tissues, Systems
1. $+G_z$ Feet First (N=34 individuals)  Totals:[1]	11 11 individuals (32.3%)	Contusions to buttocks, thighs Friction burns surrounding legs contusions to back, chest, legs to waist, to shoulder, to entire body 23 individuals (68.7%)	Compression fracture T-12 (3 cases) Compression fracture L-1 (3 cases) Compression fractures to T-4, T-6, T-11, T-3, T-2 fracture left pubic ramus fracture tibia (midshaft) transverse fracture right femur fracture midshaft femur (bilateral) fracture humerus (bilateral) comminuted fracture right scapula fracture distal clavicle fracture 2nd metacarpal joint fracture left radius & ulna, comminuted 11 individuals (32.3%)	Shock lung hematoma (4 cases) ruptured liver* Ruptured spleen* rupture intercostal artery* pulmonary contusion pneumothorax bladder trabeculation renal hematoma tenderness, upper abdomen concussion hemorrhage right eye laceration right eye *fatal trauma, 48 Hours. 5 individuals (14.4%)
2. $+G_z$ Buttocks First (N=1 individuals)  Totals:	- (0%)	contusions buttocks & thighs individual (100%)	Compression fracture T-12, L-1 individual (100%)	renal hematoma abdominal complaints laceration nose shock individual (100%)
3. $-G_z$ Head First (N=3 individuals)  Totals:	1 1 individual (33.3%)	ecchymoses eyelids severe contusions, shoulders, thorax 2 individuals (66.7%)	- (0%)	pneumothorax, bilateral renal hematoma laceration ears bladder hematuria chest pain 2 individuals (67.7%)
4. $+G_x$ Supine (P-A) (N=2 individuals)  Totals:	- (0%)	Contusions posterior legs, back, buttocks multiple abrasions 2 individuals (100%)	fracture, compression, L-1 fracture, compression, T-12 1 individual (50%)	lung hemorrhage (1) shock 2 individuals (100%)
5. $-G_x$ Prone (A-P) (N=1 individual) 	- (0%)	multiple contusions, chest, anterior legs, abdomen, face 1 individual (100%)	- (0%)	rupture, both lungs mediastinal compression syndrome mediastinal emphysema left pneumonitis left regional pleuritis laceration right leg laceration left forearm - (100%)
6. $-G_y$ Right Side (lateral) (N=2 individuals)  Totals:	- (0%)	contusions, entire right side, Right side head & face 2 individuals (100%)	basal skull fracture (both cases) fracture, 6th rib, right possible fracture, ribs possible fracture, ribs 2 individuals (100%)	rupture, right, tympanic membrane renal hematoma painful upper quadrant laceration right leg 2 individuals (100%)

[1] Totals add up to over 100% because some individuals had trauma in more than one classification

FIGURE 5. Incidence of Trauma in Extreme Water Impacts.