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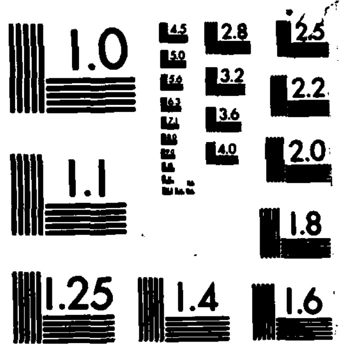

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FALL ARREST AND POST-FALL SUSPENSION: LITERATURE REVIEW AND DIRECTIONS FOR FURTHER RESEARCH

BERNARD F. HEARON, Maj, USAF, MC, FS
JAMES W. BRINKLEY

APRIL 1984

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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NOTICES

TECHNICAL REVIEW AND APPROVAL

AFAMRL-TR-84-021

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

JAMES C. ROCK, LT COL, USAF BSC
Associate Director
Biodynamics & Bioengineering Division
Air Force Aerospace Medical Research Laboratory

ERRATA SHEET

TR-84-021

	Delete	Replace with
Page 4, paragraph 4, line 4, word 7,	artifical	artificial
Page 6, paragraph 1, line 2, word 1	Oumans	humans
Page 10, paragraph 1, line 5, word 4	study (Heisner, 1965).	study.
Page 11, paragraph 1, line 1, word 6	uterus	uterus.

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prolonged motionless suspension may be due to dependent venous pooling as the result of failure of the muscle pump to return venous blood to the heart. Directions for further research in this area are provided.

PREFACE

This report is a product of the Biodynamics and Bioengineering Division of the Air Force Aerospace Medical Research Laboratory (AFAMRL). The research effort was accomplished under project 7231, "Biomechanics of Air Force Operations: Effects of Mechanical Force on Air Force Personnel." The document is a summary of a presentation made to the United States Technical Advisory Group of the International Standards Organization on Fall Protection Equipment on 16 March 1984.

The assistance of numerous individuals made this report possible. We are grateful to Mr. Terry Schmidt, President of the Rose Manufacturing Company, for providing numerous references for review and for arranging our meeting with Dr. Maurice Amphoux in October 1983. Thanks to Ms. Marjorie Task for obtaining additional references through the Air Force Wright Aeronautical Laboratories Technical Library and the Defense Technical Information Center. We are also grateful to the translators including Mr. Kevin Kearney of the Rose Manufacturing Company and the numerous translators in the Foreign Technology Divison at Wright-Patterson AFB who provided French to English translations of numerous technical documents.

The USAF occupational fall data were provided by personnel at the Air Force Inspection and Safety Center, Norton AFB, California. Thanks are offered to Mr. Dwayne Burks, Chief of the Occupational Safety Branch and Capt Steve Thomas. We are also grateful to Mr. Vince Clark of the Safety Analysis Branch at AFISC for providing the aircrew mortality data. In addition, we are also indebted to personnel at the Air Force Manpower and Personnel Center, Randolph AFB, TX, particularly those in the Rated Analysis Section. Data provided by AFMPC were used to define our populations at risk in this study.

Very special thanks are reserved for 2Lt Rickard S. Hawkins, Jr., for his assistance in reviewing and summarizing the available literature during his medical externship at AFAMRL in May-June 1983.

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SUMMARY

The available literature on fall arrest and suspension tests involving live animals or humans was surveyed. Experience in this area was found to be very limited. Experimental findings are not documented at all in the primary scientific literature nor are they well documented in the secondary literature. The available test data indicate that human suspension tolerance is a function of the restraint harness used to suspend the subject. The pathophysiologic mechanisms of injury associated with fall arrest and prolonged motionless suspension are not well defined in the available literature.

A review of Air Force occupational falls from 1978 to 1983 revealed that relatively few personnel were involved in falls resulting in death or serious injury. In fact, the death rate of Air Force personnel due to falls was estimated to be 20 times less than the death rate of Air Force personnel due to aircraft mishaps. Most of the falls in the sample studied were attributed to safety infractions by the victims. Furthermore, few of the falls appeared to be amenable to prevention by fall protection equipment.

It is theorized that the clinical findings associated with prolonged motionless suspension may be due to dependent venous pooling as the result of failure of the muscle pump to return venous blood to the heart. Directions for further research in this area are provided.

INTRODUCTION

A review of the literature on fall arrest and post-fall suspension was undertaken in response to a request by the United States Technical Advisory Group of the International Standards Organization (ISO/TAG) on Fall Protection Equipment. The study also included an evaluation of recent occupational falls among Air Force personnel. This report documents the results of the study which were presented to the ISO/TAG on Fall Protection Equipment at Wright-Patterson Air Force Base, Ohio on 16 March 1984.

An extensive search of the English-language literature was conducted using a variety of sources including the Defense Technical Information Center. Several French-language references were provided by Mr. Terry Schmidt of Rose Manufacturing Company. Those reports concerning animal or human experimentation in this area were identified and carefully evaluated.

Several difficulties were encountered in this effort. Obtaining and appropriately interpreting French to English translations of some references proved to be challenging. Also, reports on some fall arrest and suspension tests were not identified as such in the title. These latter references were difficult to access.

DEFINITIONS

Restraints which are used to arrest falls are known as containment devices. Three categories or types of containment devices will be referred to in this document. The first category consists of a simple body belt around the waist or thorax. This wide belt, made from artifical textiles or leather, has a friction or tongue buckle which is used to adjust the belt to obtain a comfortable taut fit around the torso. All containment devices are equipped with a D-ring, located in the front or back or on the side, for lanyard attachment. The D-ring of the simple body belt is usually located in the back.

The second category of containment devices consist of those having more than one strap. The thoracic or chest harness is comprised of a belt around the chest connected by shoulder straps. In this type of containment device, the fall arrest and suspension pressure is exerted on the more resistant thorax rather than on the abdomen as in the case of the waist belt. The D-ring used for lanyard attachment is usually located dorsally.

The third type or category of containment device is referred to as a full body harness. The basic full body harness consists of leg straps which support the upper thighs and pelvis, shoulder straps, and a waist belt or chest strap. There are several varieties of full body harnesses including those used by mountain climbers and parachutists.

OBJECTIVES

The objectives of the present study are summarized as follows.

1. To provide a concise and comprehensive review of the available literature on fall arrest and suspension experiments involving animal surrogates and live human subjects.

2. To determine the number of recent occupational fall injuries and deaths among Air Force personnel and to assess the overall significance of this problem in the Air Force.

3. To provide an overall assessment of research in the area of fall arrest and post-fall suspension and to offer directions for further research.

LITERATURE REVIEW

The literature on fall arrest and suspension tests involving live animals or Oumans was surveyed. Numerous abstracts of potentially relevant articles were provided by the AFWAL Technical Library and 67 additional abstracts were made available by Mr. Andrew Sulowski. Articles were selected following review of these abstracts. Nearly 100 journal articles and reports were ultimately reviewed. These were obtained primarily from the AFWAL Technical Library and the Defense Technical Information Center but some articles, notably English translations of the French literature, were provided by the Rose Manufacturing Company. The documents cited in the reference list were found to contain information pertinent to this study. Questions arising from review of the French literature were clarified in a meeting with Dr. Maurice Amphoux at Wright-Patterson AFB in October 1983.

No attempt was made to perform a comprehensive review of the literature on parachute opening shock, although a limited discussion of this topic is presented. Therefore, it may be argued that only a subset of the pertinent literature has been reviewed. Nevertheless, the documents which were evaluated are summarized in the following paragraphs with special emphasis on the scientific limitations of the studies described.

FALL ARREST EXPERIMENTS

In 1952, Blake et al. performed animal experiments with the stated objective of determining the nature and mechanisms of injury produced by fall arrest deceleration. Seven live anesthetized dogs were used as subjects. In the experimental set-up, the dog was placed supine on a table and was restrained by a waist belt fixed by lanyard attachment to a cross member at the head of the table. A steel pin was inserted transversely through the greater sciatic foramina in order to be firmly fixed to the bony structures of the pelvis. A steel cable was attached to the pin and led distally to a pulley mechanism at the foot of the table where the cable was attached to a weight suspended by a quick release mechanism. By allowing the weight to free fall, an impulsive force was applied to the pelvis of the dog in order to simulate fall arrest.

Each dog experienced from one to five weight drops. Multiple drops occurred in rapid succession or over a period of several hours or days. Electrocardiographic tracings of one dog were reported to have shown T wave inversion, a change in R wave amplitude and Q wave variability. Five of the seven dogs succumbed to the experimental exposures and the other two dogs were sacrificed. Necropsy findings included heart dilation in all dogs, evidence of congestive heart failure in the majority of dogs and a variety of injuries to internal organs including liver, spleen and pancreas. Hepatic laceration, focal hemorrhage in the spleen and pancreas and hemorrhage in the abdominal wall were observed autopsy findings which may have been due to the direct trauma of the waist belt.

Several mechanisms were proposed to explain the cardiac findings at necropsy. The authors suggested that the abdominal viscera were pushed up against the diaphragm and delivered a blow to the heart during the fall arrest. In order to obtain further insight into the mechanism of injury, additional experiments were carried out. Live dogs were restrained by a waist belt to a metal frame which moved along a vertical I-beam. The animals were allowed to free fall 5.5 ft and radiographs of the animals were obtained at a rate of 50 per second.

An analysis of the x-rays revealed that 25% of the dogs (total number in the experiment not specified) had diffuse cardiac enlargement or enlargement of the pulmonary artery segment or both. None of the dogs were autopsied. The authors concluded that significant stretching of the heart muscle secondary to transient cardiac enlargement during fall arrest can result in permanent cardiac damage.

Several limitations in this study were noted. For example, in the first phase of testing the drop weight used for application of impulsive force to the animals was not specified. Neither the impulsive force applied through the cable nor the tension developed in the waist belt lanyard were measured. The reason for multiple exposures of some of the animals was not explained. The electrocardiographic tracings documented in the report were uninterpretable. Finally, the total number of dogs used in the second phase of testing was not specified.

The French have documented limited fall arrest and suspension tests repeatedly in the secondary scientific literature. The fall arrest tests involving human subjects were conducted by Noel and Amphoux and associates in about 1970 (Amphoux, 1982a,b; Ardouin, 1972; Noel et al., 1978). The purpose of these experiments was to determine the maximum fall arrest force subjectively tolerable to human subjects. Human volunteers, including Amphoux himself, were dropped distances up to 0.66 m while wearing a mountain climbers' harness with a dorsal lanyard attachment. A cushion of felt 12 mm thick was placed between the body and restraint. A stuntman wearing a leather vest was dropped up to 0.8 m while similarly restrained in a waist belt with shoulder straps.

Approximately 30 fall arrest experiments in all were conducted (Amphoux, personal communication). The maximum arresting force measured during the experiments was 4800 N at 0.8 m fall distance. The maximum acceleration recorded was 7 G. Amphoux suffered two fractured ribs in a fall from 0.5 m and the stuntman declined further tests after thoracic contusions were noted in the area under the thoracic belt following a 0.8 m fall. As a result of these experiments, the French concluded that the maximum arresting force, rather than the fall height, was the critical factor in determining human tolerance to fall arrest. Furthermore, they proposed a limit of 2000 N as the maximum permissible arrest force. A specific schedule of the drop tests was not included in any of the reports on these experiments.

Ulysse et al. (1978) has apparently conducted a variety of fall arrest experiments involving human subjects. However, the documentation of the physiologic responses of the subjects participating in these tests is limited. One subject, age and sex unspecified, tolerated a drop of 2 m while restrained in a full body harness with a shock-absorbing dorsal lanyard. Maximum measured acceleration was 3.3 G. No further details were provided.

In the United Kingdom, a limited number of fall arrest and suspension tests involving human subjects was conducted (Beeton et al., 1968). These tests were done in order to determine the acceptability of a torso harness for use in the British type 9 ejection seat. Anticipated "snatch" loads occurring on parachute deployment during the ejection sequence were simulated by drop tests of volunteers. Three subjects in full flight gear including G-suit were restrained in the personal torso harness used in the Phantom F-4 aircraft. Seven tests were accomplished. The pre-test weight of each subject was determined, loads in the riser straps were measured by strain gages during each fall and then the peak acceleration experienced by each subject was calculated. This acceleration varied from 5 to 12 G. Axillary pain was noted by a subject in one test but was attributed to incorrect harness adjustment. Some "head whip" was noted in three tests. The investigators concluded that the torso harness functioned satisfactorily as a parachute harness. Subjects also underwent a period of post-fall suspension and provided subjective comments on harness comfort during that period. The times of post-fall suspension, however, were not specified. In addition, the drop height was predetermined, but not specified, and the loads measured in the riser straps during the falls were not reported. Documentation of this study is, therefore, inadequate.

HUMAN SUSPENSION TESTS

Very little research has been accomplished in the area of human suspension. About 1978, the French conducted several tests to determine human tolerance to suspension in various harnesses. This work was originally reported by Noel et al. (1978) and additional comments on the research were provided later by Amphoux (1982a,b). Five subjects aged 18 to 59 years with no special qualifications agreed to participate in the study. The subjects were instructed to hang passively in the restraint to simulate an unconscious post-fall victim. Six harness configurations were evaluated including three torso harnesses, a parachute harness, a waist belt with shoulder straps, and a thoracic belt. Subjects were suspended from dorsal lanyard attachments.

A total of 22 tests was accomplished. It is not clear why all five subjects were not evaluated in all six test conditions. The mean suspension time for the five subjects in the four full body harnesses ranged from 19 min 47 sec to 27 min 14 sec. The shortest suspension time for a subject in a specific full body restraint was 8 min, while the longest suspension time was 43 min 15 sec. The two subjects evaluated in the waist belt with shoulder straps tolerated suspension for 1 min 21 sec and 3 min. The two subjects suspended in the thoracic belt also had limited tolerances of 1 min 20 sec and 1 min 35 sec. The investigators concluded that suspension tolerance in a specific harness varies among subjects and also that subjects may achieve maximum suspension tolerance in different restraint harnesses.

A number of adverse medical effects were encountered in this study. These included upper or lower extremity numbness; abdominal, shoulder or groin pain presumably at strap contact points; respiratory distress; nausea; dizziness; and a variety of arrhythmias. Amphoux (personal communication) has indicated that the arrhythmias included tachycardias, bradycardias, and premature ventricular contractions. A review of the data presented by Noel et al. (1978) suggested that most suspensions resulted in a tachycardia. Electrocardiographic findings typically included an increase in S and T wave amplitudes and a decrease in R wave amplitude.

Several shortcomings were noted in this study. The gender of the subjects was not specified and EKG traces were uninterpretable. In addition, a clear pathophysiologic mechanism for the adverse medical effects was not established. In the numerous reports and discussions on these experiments it was suggested that the responsible mechanism may have a respiratory, cardiac or circulatory basis. Furthermore, Amphoux (personal communication) expressed reluctance to conduct further human suspension tests for fear of adverse medical consequences.

In 1979, Nelson published the results of human suspension tests conducted to determine the effects of suspension in mountain climbers' harnesses. In so doing, he noted the absence of previously published research in this area. Ten volunteer men and women, all highly experienced or professional mountaineers, participated in the experiment. The subjects were instructed to avoid moving during the period of suspension. Seven harness configurations commonly used by climbers were evaluated. These included the REI Sit harness, Whillans harness, Winter One, Edelrid Futura, Troll Body, Swiss seat and bowline-on-a-coil.

A total of 65 tests were accomplished. Five of the potential maximum 70 tests were not done due to problems obtaining satisfactory harness adjustment in the five cases. Mean suspension times ranged from 24 sec for the bowline-on-a-coil to 17 min 21 sec for the REI Sit harness. The maximum suspension time for any subject was 28 min in the Edelrid Futura.

A variety of medical adverse effects were encountered in the 65 tests. These included lower body numbness (25 cases), intense pain (21), respiratory distress (8), uncontrollable shaking (4), change in blood pressure (3), loss of consciousness (2), weak pulse (1), and upper body numbness (1). The two cases of loss of consciousness occurred despite the investigator's efforts to terminate the suspension prior to loss of consciousness. The suspensions were also terminated in the event of severe pain, tachycardia, extremity numbness, or narrowing of the pulse pressure.

This study concluded that hanging vertically in a harness can cause loss of consciousness without prior trauma or blood loss. It was suggested that climbing harnesses should permit a horizontal body orientation during suspension. A higher incidence of respiratory distress was noted when a Swami type configuration around the waist was used for partial support of the climber's weight and in those restraint configurations which restricted chest expansion during respiration. Although vital signs were taken every two minutes during these suspensions, they were not reported in the study. In addition, no specific pathophysiologic mechanism for the adverse medical effects observed during the tests was proposed.

About 1968, several human suspension tests were conducted at the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base. These were done in order to determine the maximum suspension times for subjects restrained in an F-4 or F-105 ejection seat. At least four male subjects in full flight gear participated in the study (Hiesner, 1965). There were probably no restrictions on subject movement during the time of suspension. Participants were restrained in a PCU-15/P torso harness and lap belt arrangement and their legs were strapped to the lower portion of the ejection seat. The seat-man combination was then suspended in various orientations, including one in which the subject faced downward, arms dangling, with the long axis of the vertebral column parallel to the laboratory floor. In these tests, all subjects tolerated suspension for 28 to 30 minutes. However, the results of this study were never published in the technical literature.

Other military experience in this area is related to operational use of the Fulton Recovery System (Skyhook). This system of ground-to-air rescue (Heisner, 1965) has been used for more than 25 years to recover military personnel from tactical land and water areas. The rescuee is restrained in a parachute harness. A 600 ft dorsal lanyard, held aloft by balloon, is captured by a low-flying aircraft traveling at approximately 150 knots. The crewmember is towed and eventually hoisted aboard the aircraft. Snatch loads are well tolerated and the in-flight suspension during reel-in (usually 4 to 10 minutes in duration) is also tolerated by the rescuee with little difficulty. Sixty-seven rescues from a variety of locations including the North Pole were accomplished between August 1958 and January 1965 and were documented by the Robert Fulton Company of Newton, Connecticut. Many additional pick ups have been completed since that time.

ASSESSMENT

After a thorough review of the available literature, it may be concluded that experience with human fall arrest and suspension tests is extremely limited. Experimental findings are not documented at all in the primary scientific literature. Furthermore, those experimental results which are seen in the secondary literature are not well documented. Translations from the French literature were often difficult to obtain and interpret.

Nevertheless, some tentative conclusions may be drawn based on our knowledge of response to whole body impact in various restraint configurations. It is well established that the lap belt alone is a less adequate forward facing impact protection device than, for example, a double shoulder strap and lap belt arrangement. Clarke et al. (1970, 1972) conducted a series of forward facing impacts using anesthetized baboons as subjects. He found that the impact level required to produce fatal injury in 50% of the subjects was considerably less when the lap belt alone was used for restraint than when the double shoulder strap and lap belt arrangement was used. Snyder et al. (1969a), in similar experiments with anesthetized baboons, observed that significant injuries were associated with use of the lap belt only restraint including contusions of the anterior abdominal wall and hemorrhages in multiple organs such as the brain, heart, spleen, pancreas, kidneys and uterus The lap belt may impinge against the anterior abdominal wall during a forward facing impact causing a variety of serious internal injuries including rupture of the small bowel, spleen, bladder, aorta or gravid uterus; contusion of the kidneys or small bowel mesentery; or laceration of the pancreas (Snyder et al., 1969b). Fractures of the ribs, pelvis or lumbar vertebrae (tension-type) have also been associated with lap belt only restraint. On the basis of these data, it may be reasonably concluded that the risk of fall arrest injury with a waist belt is probably greater than the risk of fall arrest injury with a full body harness, assuming a dorsal lanyard attachment is used in both cases.

It also appears that human tolerance to suspension is a function of the restraint harness used and the manner in which the harness is adjusted. Despite the limited data available on human suspension, it appears that the waist belt and thoracic harness are not useful for prolonged motionless suspension. Further human suspension tests with the waist belt, thoracic harness or bowline-on-a-coil should be approached with great caution and only if the benefits of such an investigation can be demonstrated to outweigh the risks. Human suspension tests in full body harnesses, however, may be useful as a means of characterizing the merits of various full body restraint systems.

Finally, it is clear that the mechanisms of injury associated with fall arrest and prolonged motionless suspension are not well defined. Respiratory, cardiac and circulatory derangements have been suggested as responsible mechanisms limiting human suspension tolerance.

USAF FALL EXPERIENCE

This phase of the study was undertaken to determine the number of recent job-related falls in the Air Force and to assess these falls as an occupational safety problem. In addition, the recent USAF injury experience associated with parachute opening shock was reviewed. The ultimate objective here was to define future USAF research requirements in the area of fall arrest and post-fall suspension.

OCCUPATIONAL FALLS

Information on all falls resulting in death or permanent disability between 1978 and 1983 inclusive was obtained from the Air Force Inspection and Safety Center (AFISC) at Norton AFB, California. During that six year period, there were 12 incidents involving 13 victims (10 civilians, 3 military). The job titles and ages of the victims as well as mishap and injury descriptions and associated safety infractions are summarized in Table 1. The average age of the victims was 40.8 years. Seven victims were fatalities and the remaining six suffered injuries resulting in permanent disability.

There are two significant observations regarding these data. First, the majority of falls in this sample (9 of 13) may be attributed to safety infractions by the victims. The infractions ranged from failure to heed safety warnings to the ill-conceived use of a 30-inch window ledge as a work platform. Second, the minority of falls in this sample appeared to be amenable to prevention by fall protection equipment. In one case, the improper use of a lineman's belt was apparently responsible for a fall fatality.

To achieve a better perspective on the occupational fall problem within the Air Force, the death rate due to falls was compared to the more familiar casualty rates among aircrew members. The job title and associated Air Force Specialty Code (AFSC) of each fall victim were used to define the population at risk. The number of personnel assigned to each of the 10 job categories involved (Table 1) was obtained from the Air Force Manpower and Personnel Center (AFMPC) at Randolph AFB, Texas. These numbers for end FY83 were summed to obtain the total population at risk of 15,082 cited in Table 2.

The limitations associated with this approach to defining the population at risk are recognized. For example, not all Air Force employees in a given job category or AFSC will necessarily be performing duties placing them at risk for fall injury or death. This would lead to an overestimate of the population at risk. However, personnel in other job areas are probably also at risk for fall injury or death and the exclusion of these personnel would necessarily lead to an underestimate of the population at risk. At any rate, the population of approximately 15,000 represents our best estimate of those at risk for fall injury or death annually. Since the manpower allocations are reasonably constant in these career fields from year to year, we assumed that the same number of personnel were at risk during the period from 1978 to 1983. On the basis of these data, the calculated death rate is 8 per 100,000 person-years. This rate is in agreement with the fall death rate of 6.7 per 100,000 persons quoted for the general United States population in 1976 (Snyder, 1977).

TABLE 1. FALLS AMONG AIR FORCE PERSONNEL RESULTING IN DEATH OR PERMANENT DISABILITY (1978-1983).

JOB TITLE	AGE	MISHAP DESCRIPTION	INJURY	SAFETY INFRACTION
Carpenter	62	Fell from scaffold	Fatal	
Carpentry helper	52	Fell between ceiling rafters	Fatal complications 4 months post-injury	Stepped on unsecured plywood
Aircraft mechanic	49	Fell from maintenance work stand while servicing a KC-135.	Fractured spine	Work stand guard rail not secured.
Aircraft mechanic	33	Fell from maintenance work stand while servicing a C-141. Platform extension failed at hinge pin.	Fatal	
Wire communications specialist	23	Fell from utility pole	Fatal	Utility pole pulled down as passing sanitation truck caught sagging cable
Industrial equipment mechanic	27	Fell from ladder while servicing steam valve	Fractured spine	Improper use of ladder; one foot on ladder, other on pipe.
Maintenance mechanic	49	Fell from window ledge while installing glass window	Fatal	Used 30-inch-wide window ledge as work platform without safety device.
(Unknown)	52	Fell from scaffold while removing auditorium decorations	Multiple extreme injuries	Co-workers moved scaffold with mishap worker standing on it.
Metal fabricating helper	21	Fell from overhead door when it suddenly closed.	Fractured both arms	
Welder	49	Fell from overhead door when it suddenly closed.	Fractured skull	
Testing equipment operator	35	Fell from wing of F-15A while x-raying wing flap.	Lost sight, right eye	Wing flap tenuously supported by maintenance work stand and broom handle. Worker did not heed caution warning.
Carpentry helper	23	Fell from attic between rafters while repairing ceiling tiles	Fatal	Worker did not heed caution warning.
Electrician	56	Fell from utility pole	Fatal	Safety loop of lineman's belt disconnected.

Source of Data: Air Force Inspection and Safety Center (Norton Air Force Base, California).

TABLE 2. COMPARISON OF AIR FORCE FALL VICTIMS TO AIRCRAFT ACCIDENT CASUALTIES (1978-1983)

PARAMETER	FALL VICTIMS	AIRCREW CASUALTIES PILOTS	AIRCREW CASUALTIES OTHER CREW MEMBERS
Deaths	7	268	170
Estimated Population at Risk	15,082	23,027	17,243
Death Rate (Per 100,000 Person-Yrs)	8	194	164

Sources of Data: Air Force Inspection and Safety Center (Norton Air Force Base, California) and Air Force Manpower and Personnel Center (Randolph Air Force Base, Texas).

The number of fatalities due to aircraft accidents among USAF pilots and other crewmembers from 1978 to 1983 was obtained from AFISC. Fatalities included personnel on active duty and those in the Air National Guard (ANG) or Air Force Reserve (AFR). The population at risk for death in operational flying mishaps was obtained from AFMPC. These data included all active duty flying personnel as well as pilots and navigators assigned to the ANG or AFR. Personnel strength data on other aircrew members (such as flight mechanics and load masters) assigned to the ANG or AFR were not readily available.

Several assumptions were made in defining the population at risk. For example, it was assumed that 75% of active duty pilots and 70% of active duty navigators were engaged in flying activities. On the other hand, 85% of the pilots and navigators in the ANG or AFR were assumed to be engaged actively in flying duties. The estimated populations at risk and associated death rates for pilots and other crewmembers are shown in Table 2. It should be noted that death rates of aircrew members are usually expressed in terms of fatalities per 100,000 flying hours. We recognize this as a more desirable form of presentation. However, since data were not available to allow calculation of the comparable death rate for fall victims, the unadjusted death rate per 100,000 person-years is presented for fall victims, pilots and other crewmembers.

These data indicate that relatively few Air Force personnel have died as the result of occupational falls during the period of study. Generally, the fall victims were older than the more highly trained personnel who are casualties in flying operations. On the basis of these data, the death rate of Air Force personnel due to falls is estimated to be 20 times less than the death rate due to aircraft mishaps. This does not indicate that the occupational fall problem within the Air Force is insignificant. Rather, these data imply that biomechanical protection issues related to flying safety should have a higher priority within the Air Force than research devoted solely to fall arrest in view of the limited USAF resources available in biodynamics research.

PARACHUTE OPENING SHOCK INJURIES

Military interest in fall arrest and post-fall suspension is based largely on the requirement to provide protection for personnel at risk of injury from parachute opening shock. These personnel include paratroopers and aircrew members who must eject from disabled high-performance aircraft. Review of recent injury trends among these personnel may help define the operational need for improved protection against parachute opening shock. This need may then be used to help formulate biomechanical research priorities.

The overwhelming majority of injuries incurred by paratroopers are apparently due to landing impact. In a retrospective study of 83,718 consecutive parachute jumps, Hallel & Naggan (1975) documented 250 serious injuries (0.3%). Most of these injuries were fractures of the long bones of the leg, fractures of the ankle or fractures of the foot. The authors attributed over 90% of the injuries to parachute landing fall rather than parachute opening shock. This experience is expected in view of the mild maximum arresting force generally imposed on the parachutist during a premeditated parachute jump.

The injuries associated with parachute opening shock during emergency escape from high-performance aircraft have usually represented a relatively small percentage of the total injuries due to ejection, even in the combat ejections which occurred in Southeast Asia. Use of the newest USAF ejection system, Advanced Concept Ejection Seat (ACES II), however, has been encouraging in this regard due to the absence of parachute opening shock injuries in the 72 ejections which have occurred to date. Several features of the ACES II are believed to be responsible for this improved performance (Douglas Aircraft Company Report MDC J4576A). These include improved aerodynamic stability of the seat, canopy reefing and lines first deployment of the recovery parachute, and the sequencing of the man-seat separation. Parachute deployment occurs prior to man-seat separation in order to assure proper crewmember alignment at the time of deployment and to avoid man-seat contact following man-seat separation.

ASSESSMENT

Therefore, there appears to be no compelling evidence to place a high priority on research in the area of fall arrest and post-fall suspension within the Air Force. This conclusion is supported by the relatively small number of occupational falls resulting in death or serious disability during the last six years in the Air Force compared to the larger number of fatalities resulting from aircraft accidents during the same time period. This assessment is also supported by the absence of parachute opening shock injuries associated with operational use of the ACES II.

DIRECTIONS FOR FURTHER RESEARCH

Although research in the area of fall arrest and post-fall suspension does not have a high priority within USAF, additional research is clearly indicated. The field of fall protection appears to be fertile for investigations designed to identify the pathophysiologic mechanisms of injury associated with fall arrest and suspension. Future efforts should be based on the scientific method, beginning with the formulation of hypotheses amenable to experimental evaluation.

Proposed mechanisms of fall arrest injury may be difficult to confirm. However, experimentation with animal surrogates may be helpful in establishing the mechanisms which limit tolerance to fall arrest. Animal drop tests using various containment devices may establish the alleged inadequacy of the waist belt in preventing serious internal injury during fall arrest.

PATHOPHYSIOLOGY OF PROLONGED SUSPENSION

The static environment associated with prolonged motionless suspension appears to be more amenable to investigation. As previously noted, the pathophysiology associated with prolonged suspension has not been well defined. Amphoux has suggested that the basic underlying derangement may be respiratory, cardiac or circulatory in origin.

We hypothesize that the fundamental pathophysiologic mechanism responsible for the clinical adverse effects associated with prolonged suspension is venous pooling in the dependent lower extremities due to failure of the venous or muscle pump to operate during the period of motionlessness. Recall that the volunteers who participated in previous suspension tests (Noel et al., 1978; Nelson, 1979) were required to avoid movement in order to simulate an incapacitated post-fall victim. Without muscle contraction in the lower extremities, venous pressures in the legs will rise rapidly. Capillary pressures will also rise and fluid will leak from the circulatory system into the tissue spaces. Approximately 20% of the blood volume may be sequestered in this manner within 15 minutes (Guyton, 1981). The consequences of this phenomenon are commonly seen on the parade grounds when recruits standing at attention for prolonged periods lose consciousness. This occurs as the result of venous pooling in the lower extremities.

The pathophysiologic consequences of peripheral venous pooling include decreases in central venous pressure, venous return to the heart and cardiac stroke volume. These parameters may be measured in animal subjects during suspension tests. Other consequences include tachycardia, decreased pulse pressure, weak pulse, inadequate tissue perfusion, blackouts and loss of consciousness. These clinical findings have been observed in the human suspension tests previously discussed. Peripheral venous pooling due to failure of the muscle pump to return blood to the heart may, therefore, be the mechanism responsible for limiting human tolerance to vertical suspension in full body harnesses.

Suspension in a waist belt may produce direct compression of the abdominal viscera and the inferior vena cava leading to a similar phenomenon. Suspension in the waist belt or thoracic harness may interfere with respiratory mechanics leading to respiratory distress and the potential for hypoxia. It is unlikely, however, that this mechanism plays a major role in limiting tolerance to suspension in full body harnesses.

INVESTIGATIVE APPROACH

Efforts should first be directed to defining the pathophysiologic mechanisms of injury associated with fall arrest and post-fall suspension. Experiments with animal models to define the consequences of prolonged motionless suspension in various restraint configurations may provide useful information in this regard. These pathophysiologic insights may then be used to eliminate inadequate fall containment devices and to modify marginally adequate restraint configurations as necessary.

Finally, promising restraint configurations (full body harnesses) may be evaluated by performing human suspension tests under careful medical supervision. A comparative approach may be used to distinguish the best harness among several alternatives. Again, further suspension tests of volunteer subjects using the waist belt or thoracic harness should be approached with great caution and only if anticipated benefits of the proposed experiments can be demonstrated to outweigh the risk associated with this exposure.

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