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ARMSTRONG LABORATORY

DEVELOPMENT OF A COMPREHENSIVE NECK INJURY CRITERION FOR AIRCRAFT-RELATED INCIDENCES

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FINAL REPORT FOR THE PERIOD MAY 1994 TO FEBRUARY 1995

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Current manikin testing and accident investigations may be inadequate to fully assess the potential for human injury in novel aircraft and automobile dynamic situations. An injury assessment system is needed that will relate manikin-based loading information to specific human injury predictions (injury type, severity, and probability). This system may consist of an instrumented manikin, manikin to human correlations, and a human injury criterion. The principal objective of this Phase I Small Business Innovative Research (SBIR) program was to develop the injury criterion for the human neck in axial compression. To develop the criterion, injury-producing situations from military mishaps were reviewed from literature, military databases, and individual Air Force mishap records. Neck-injury producing loads from approximately 35 experimental references were collected. A branched structure was developed to relate loading inputs (primary and off-axis loading directions, loading magnitude, and subject history) to injury outputs (injury mechanism, injury severity, injury location, and experimental references). This branched structure can be applied to other loading directions and other body segments and allows each criterion to be readily updated as new experimental and injury information becomes available.

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EXECUTIVE SUMMARY

Currently, safety systems for aircraft and automobiles are assessed proactively by performing tests with manikins and retroactively by investigating situations in which humans are injured. Proactive tests with manikins are currently limited to a general assessment of injury likelihood from the loading information measured by the manikin. These assessments do not necessarily have an anatomical meaning, nor are specific mechanisms or locations of injuries predicted. Retroactive investigations, on the other hand, will provide information on the mechanism or location of injury; however, the loads and accelerations experienced by the human during the mishap may not be known.

As technology advances, the loads and accelerations experienced by humans in dynamic situations continually change. Therefore, it has become increasingly more important to better understand the specific injuries and possible consequences of loads applied to humans. An injury assessment system is needed that will relate either manikin-based or human-based loading information to the types of injury information obtained from actual mishap investigations. This all-encompassing system would involve a manikin or another means of obtaining loading information, a correlation of that data into human terms, and an injury criterion that relates the loading data to the specific injuries that would be expected to be produced.

The principal objective of this Phase I Small Business Innovation Research (SBIR) program was to develop one component of the three-part Injury Assessment System; that is, the injury criterion. A basic injury criterion structure was designed, and a portion of an comprehensive neck injury criterion was developed. The approach to developing the three-part injury assessment system was also defined.

The method used to accomplish the objective of the Phase I program was to identify the neck injuries that typically occur in military aircraft mishaps and to correlate these injuries with the most likely mechanisms or causes of the injury. A neck injury criterion was developed by incorporating this information into a comprehensive, branched structure.

Injuries that typically occur in military aircraft mishaps were identified from medical and military mishap literature and through a first-hand review of U.S. Air Force Safety Agency database records and individual mishap files. Injury rates from U.S. Naval helicopter and fixed-wing aircraft crashes and from U.S. Army helicopter crashes were identified in the literature. Together, these statistics indicate that military aircraft-related injuries occur predominantly to the head, spine and extremities. Thoracic spine fractures were the most frequent injury to occur in Air Force ejections. While neck sprains and strains were also frequent, neck fracture was not a significant occurrence. Interestingly, the rate of thoracic spine injuries is significantly reduced with the use of ACES II ejection seats. The rate of cervical spine fractures also decreases.

Sixty-four mishap files were reviewed at the Air Force Safety Agency. These files were reviewed to obtain information regarding the cause of an injury or the mishap scenario in which an injury occurred (see Appendix A). All injuries that occurred to the head, spine, neck, and extremities were considered. Injury tolerance information such as occupant loads or accelerations was not typically available in the files. To develop a neck injury criterion, the mechanisms of injury and corresponding injury-causing loads had to be determined.

Therefore, experimental neck data from approximately 35 references were thoroughly analyzed.

Eleven neck injury directions were identified from the literature. These directions include axial compression, axial tension, flexion, extension, horizontal shear, rotation, lateral bending, compression-extension, compression-flexion, tension-extension, and tension-flexion. For each direction, one to six different injury mechanisms were identified. Typical neck or vertebral injuries were described as ligamentous injuries, hyperflexive strains, avulsion fractures, transverse ligamentous ruptures, wedge fractures, teardrop fractures, burst fractures, or hangman's fractures, etc. Appendix B defines each of these loading mechanisms and injuries.

Neck-injury-producing load magnitudes were also determined from the experimental data found in the literature. An extensive database was developed to store the load information obtained from each reference (see Appendix C). The data was then compiled and analyzed. Several considerations were made prior to selecting the most appropriate data for the neck injury criterion. These considerations were based on the varying test conditions between the experiments. Typical variations in the test conditions include the following:

1. The different specimen types that were tested included live volunteers, whole cadavers, cervical spines, functional spinal units, and single vertebrae.

2. The neck loading rates in the tests ranged from static loading to dynamic or impulse loading.

3. The condition of the volunteers or cadavers varied according to their ages, fitness levels, and health.

4. The loading protocol was complicated by the complexity of the cervical spine; small loading changes could significantly affect the results.

Each of these conditions was incorporated into the neck injury criterion in the form of a series of inputs. The data obtained from the literature was then incorporated into the branched neck injury criterion structure. The neck injury criterion consists of a series of input conditions that dictate the output injury information. The required inputs include primary loading directions, off-axis loading conditions, the loading rate or duration, subject factors (average or vulnerable), and load magnitude. Each branch of the neck injury criterion leads to an output injury mechanism, injury severity, and injury location. The document from which the data was obtained is referenced with each injury output. Overall, the injury predictions were very conservative. A branched injury criterion has been developed for pure axial compression, compression with flexion, compression with extension, and compression with eccentricity. Each of these neck injury criterion sub-branches may eventually be commingled into one complete, branched neck injury criterion. A software program will be necessary to accommodate such a complex injury criterion structure as this.

This branched neck injury criterion has been developed to provide the maximum amount of information to the user. The branched structure is designed to be readily updated as new experiments and tolerance information becomes available. The neck injury criterion and future developments of injury criteria for other body segments will eventually be incorporated into a three-part injury assessment system. This three-part injury assessment system will measure loads and accelerations experienced by a manikin in a dynamic environment and then relate the measurements to the injuries which a human would experience in the same situation. The development of the injury assessment system relies heavily on experimental and medical data such as that obtained in this Phase I program for the development of the neck injury criterion. The injury assessment system also relies on novel correlations between the manikin measurements and the human-based data to be able to use manikins as accurate predictors of injury in humans. The biofidelic status of manikin technology will also play a critical role in how the injury assessment system is designed. Since the injury assessment system is formulated in three components, the system can be upgraded with advancements in any one of its three component areas.

For example, computer and analytical models may eventually be used to incorporate experimental information from individual vertebrae and functional spinal units into the injury criteria. This technological advancement would eventually reduce the need for cadaver and volunteer testing. Recent technological advances in artificial intelligence, such as neural networks, may also provide a means by which to incorporate a measure of probability into the injury assessment system.

This all-encompassing injury assessment system, which incorporates the neck injury criterion developed in this program and utilizes the method for developing injury criteria for other body segments, would advance the state of the art in safety technology development.

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1.0 INTRODUCTION

1.1 INTRODUCTION TO THE PROBLEM

Currently, safety systems for aircraft and automobiles are assessed proactively by performing tests with manikins and retroactively by investigating situations in which humans were injured. Manikins are often used to evaluate dynamic situations where there is considered to be a potential risk of injury for a human. For some body segments, injury criteria exist that relate the loads and accelerations measured by the manikin to the level of injury that would be experienced by a human in the same situation. However, these injury criteria do not necessarily have anatomical meaning, nor do they predict specific injury mechanisms or locations. Specific injury mechanisms and locations may be obtained from the field data of mishap investigations. While this information is valuable, it is insufficient for design and research purposes, because the loads and accelerations causing the injury may not have been known. The large amount of time taken to collect and evaluate field data also reduces the feasibility of this method. Currently, no single injury assessment methodology allows for the specific injury mechanisms and locations to be determined directly from either human- or manikin-based load data.

The need to understand the specific injuries and the possible consequences of loads applied to humans is increasing. As technology advances, the loads and accelerations experienced by humans in dynamic situations continually change. Specifically, as military aircraft technology advances, aircrew experience novel, and often more severe, loading situations. The trend towards helmet-mounted equipment (e.g., night vision goggles, targeting devices, and helmet-mounted displays) makes the helmet heavier and changes the center of gravity of the head, thereby producing a greater potential for neck injury during high-G maneuvering, ejections, and crash landings. Also, as limits of the ejection envelope in military aircraft are expanded, the risk to the aircrew increase. For example, at higher ejection airspeeds, the risk of injury due to windblast and flailing increases. In addition, increasing ejection survivability during low-level ejections could potentially induce novel and potentially severe loads on the occupant. For example, as the aircrew ejects and is propelled upwards away from the ground, the neck and spine may be exposed to loading conditions not previously experienced with less-advanced ejection technology.

An injury assessment system is needed that will relate either manikin-based or human-based loading information to specific human injury information; information such as can be obtained from actual mishap investigations. This all-encompassing system would involve a manikin or other means of obtaining loading information, a correlation of the loading data into human terms, and an injury criterion that relates the human-based loading data to the specific injuries that would be expected to be produced. The injury assessment system will advance the state of the art in safety technology development. The development of a human injury criterion, the first step in the development of the injury assessment system, has been initiated and is discussed in the following report.

1.2 SBIR PROGRAM GOAL

The goal of this SBIR program was to develop a comprehensive injury assessment system capability that would predict the occurrence of injuries through dynamic testing with manikins. Although injury tolerances currently exist, they are generally one-dimensional, providing design and test engineers with little information about the actual injuries that could be expected. A detailed assessment of the injury potential would allow for better evaluations of designs and, therefore, may lead to safer systems. A three-part injury assessment system would be developed to include an appropriately instrumented manikin, correlations between manikin measurements and human-based loading, and injury criteria that predict human injuries from the human-based loads. An injury criterion structure was developed during the Phase I effort of this SBIR program. Manikin instrumentation and manikin-to-human correlations will be developed in a Phase II effort and be based upon the requirements of the injury criteria.

1.3 PHASE I GOAL

The goal of this Phase I effort was to develop the human injury criteria portion of the three-part injury assessment system. A general injury criterion structure was designed and one branch of an extensive neck injury criterion was developed. The three-part injury assessment system structure was also developed in Phase I to demonstrate the integration of the injury criterion into the overall system. The injury criteria portion of the three-part injury assesment system was first addressed in this Phase I program because the criteria provide the basis for developing the other two components of the assessment system: manikin re-instrumentation and manikin-to-human based correlations. The injury criteria developed in Phase I require human-based loading inputs to predict human-based injury outputs. The criterion structure was designed to provide the user with as much information as possible regarding the input loads. Furthermore, it is a "living" structure than can be updated as improved manikin technology and new experimental evidence become available. The application of the injury criteria to the injury assessment system was shown through the development of the injury assessment system structure.

1.4 TERMINOLOGY

This section contains definitions for some of the key terms used throughout this report:

Injury assessment system - A specific set of hardware and software that relates loads experienced by a manikin to human-based injury predictions. In the future, similar injury assessment systems could be developed with computer models instead of manikins.

Injury criterion - One or more tolerances that relate the applied human-based loads to the expected human-based injury outputs; a numerical relationship between measurable engineering parameters and the injury level. (Reference 1)

Tolerance - A numerical value that demarcates a specific injury type or probability.

Injury tolerance - The magnitude of loading which can produce a specific injury type. (Reference 1)

Force tolerance - A force magnitude at which a specific injury can be expected.

Moment tolerance - A moment magnitude at which a specific injury can be expected.

2.0 PHASE I APPROACH

The Phase I approach to developing a comprehensive neck injury criterion was to first identify the neck injuries that typically occur in military aircraft mishaps and then to correlate these injuries with the most likely mechanisms or causes of injury. A neck injury criterion was developed by incorporating this information into a comprehensive, branched structure. Specifically, the Phase I effort included identifying the types and frequencies of injuries and prioritizing these injuries on the basis of rate of occurrence and injury severity; collecting and evaluating medical and experimental information on injury mechanisms and the loads that cause injuries; formulating an injury criterion structure by relating the input loads to the output injury mechanisms, locations, and severities; demonstrating the neck injury criterion through the full quantification of the axial compression branch; and then demonstrating the feasibility of the injury criteria through the development of the injury assessment system structure. Figure 1 describes this approach as a series of four separate tasks. These four tasks, and the documentation task (Task 5), are summarized here:

Task 1. Identify injury scenarios. Relevant neck-related injuries were identified from the medical and military mishap literature and through a first-hand review of Air Force Safety Agency database records and individual mishap files. Injuries considered relevant were fractures, fracture-dislocations, sprains-strains, and other serious injuries. Injuries to all body segments were considered during the literature reviews, although the Safety Agency database and record reviews focused on the neck, spine, head and extremities. Information collected included rate of injury occurrence to specific locations; injury location, type, and severity in the individual mishaps; and military mishap scenario data (e.g., aircraft velocity, altitude, attitude). Additionally, in preparation for building the neck injury criterion, the occurrence of neck injury in the general population was investigated.

Task 2. Determine mechanisms and loads related to neck injuries. Medical and injury-related literature were reviewed to determine the injury mechanisms and the loads that produce those injuries in the cervical spine. The military mishap records reviewed in Task 1 did not provide sufficient information to relate occupant loading and accelerations to the injuries produced, but served as a guide to the most pertinent injury locations and mechanisms. The collected data were stored in a database format for easy retrieval and comparison between experiments.

Task 3. Form human injury criterion structure and neck injury criterion. The human injury criterion structure was formed by defining the relationships between human-based loading inputs and human injury outputs (based upon the information collected in Task 2). The neck injury criterion was developed as a "living" structure that can be updated and revised as new experimental information becomes available. The neck injury criterion predicts various levels of injury, including different fracture types with different levels of predicted severity. The level of detail provided by the neck injury criterion was limited by the quantity and quality of available experimental research data used to develop the conditions. The axial compression branch of the neck injury criterion was fully quantified to demonstrate the applicability of injury criterion structure.

1. Identify Injury Scenarios

Review existing databases and individual mishap files from military Safety Centers to determine:

- Prevalence of injury to each body segment
- Prevalence of neck injury mechanisms and injury scenarios
- Prevalence of neck injury in the general population

Develop Scenario Database to store details from military mishap scenarios. Example:

Mishap type	Injury Location	Injury Type	Cause of Injury	Etc.
Ejection-F16	Right humerus	Comminuted Fracture	Windblast	. . .
Ejection-F4	T12 vertebra	Burst Fracture	Ejection Force	. . .

↓

2. Determine Mechanisms and Loads Related to Neck Injuries

Identify and review relevant experimental test results and research papers to determine:

- Neck anatomy
- Neck injury mechanisms
- Loads that produce neck injury

Develop Injury Mechanism Database to create textual, anatomical descriptions of injury mechanisms and other nomenclature to be used in the injury criterion development effort.

Develop Experimental Database to store details from experimentally determined mechanical properties and quantified injury mechanisms. Example:

Reference	Subject	Loading	Results	Etc.
Yamada, '73[1]	Single vertebra, wet	Ultimate Compressive Strength	1.03 kg/mm^2	. . .
Maiman, '83[2]	Cervical spine, n=5	Compression, C7 restrain	4.0 ± 2.3 kN	. . .

↓

3. Form Human Injury Criterion Structure and Neck Injury Criterion

Form criterion with the following basic structure:

- Inputs: load direction, magnitude, and rate/duration; subject history; off-axis loading
- Outputs: injury location, mechanism, and severity; references
- Concentrate on injury mechanisms prevalent in military aircraft mishap scenarios
- Base level of criterion detail on quality and quantity of available literature.

↓

4. Develop Injury Assessment System

Injury assessment system relates manikin-based measurements to human-based injury predictions.

Develop system structure with the following basic components:

- Appropriately instrumented manikin
- Manikin-to-human correlations
- Human injury criteria.

Figure 1.
Approach to building Human Injury Criteria ([1] Reference 2, [2] Reference 3)

Task 4 **Develop injury assessment system structure.** The structure for an injury assessment system was developed. The system measures the loads and accelerations experienced by a manikin, correlates the manikin- and human-based loads, and predicts the injuries that would be experienced by a human in a similar dynamic situation. The capabilities of the injury assessment criterion structure were demonstrated through their role in the injury assessment system.

Task 5 **Document the program in a final report.** This report documents the development of the general injury assessment criterion structure, the neck injury criterion, and the injury assessment system.

Details of these tasks and their corresponding results are provided in Sections 3.0 to 6.0. The remaining sections of the report (Section 7.0 to 10.0) include the Phase I program summary, program conclusions, recommendations for future program developments and applications, and references. The appendices are attached at the end of the report.

3.0 TASK 1 - IDENTIFY INJURY SCENARIOS

The goal of Task 1 was to identify and prioritize potential injuries to the whole body in military scenarios, and to the neck in particular, during military mishaps and routine civilian activities. Injuries that occur in military mishaps were identified from the available literature (Section 3.1); injuries that occur in Air Force Class A mishaps were statistically determined from existing Air Force databases (Section 3.2) and anecdotally determined from individual Air Force mishap records (Section 3.3); and cervical spine injuries that occur to the general population were identified from the available literature (Section 3.4). Incorporating this information into the injury criterion is discussed in Section 3.5.

3.1 MILITARY-RELATED LITERATURE

Injuries that occur in military mishaps were identified from the available literature. The injury rates in military scenarios were also collected from various literature sources. The literature review indicates that the rates of injury to specific body segments and the severity of observed injuries varied with each military scenario. For example, in Naval helicopter mishaps from 1972 to 1981, where 455 injuries were recorded, the most common areas of injury occurrence were the head and the extremities (Table 1). Injury occurrences to the head and legs were also most common in Army helicopter mishaps (Table 1). In general, it appears that injuries to the upper and lower extremities, as well as to the head, occur frequently. Since these statistics relate to survivable mishaps, one may expect that these injuries were not life-threatening.

Table 1.
Injury Rates from Naval Helicopter Crashes, 1972 to 1981, and Army Helicopter Crashes, 1980-1985

Naval Helicopter Mishaps[1], 1972-1981 n=455 injuries		Army Helicopter Mishaps[2], Survivable Situations 1980-1985, n=1,484 injuries		Army Helicopter Mishaps[2], All Situations 1980-1985 n=2,090 injuries	
Injured Area	Percent	Injured Area	Percent	Injured Area	Percent
Head	22.9	Legs	27.4	Head	23.8
Legs	22.2	Head	22.9	Legs	21.7
Arms	18.5	Arms	15.5	Thorax	19.1
Back	12.1	Thorax	14.3	Arms	12.3
Chest	9.5	Thoracic / Lumbar Spine	6.5	Abdomen	6.7
Neck	7.9	Abdomen	5.3	Thoracic / Lumbar Spine	6.5
		Neck	4.9	General	3.8
				Neck	3.7

Adapted from [1] Coltman, et al., 1988 (Reference 4); [2]Coltman, et al., 1989 (Reference 5)

In fatal helicopter situations, the injuries that occur are primarily located in the head and the thorax (Table 2).

Table 2. Injuries Leading to Fatalities in Army Helicopter Mishaps, 1980-1985			
Survivable Situations, n=32 injuries		All Situations, n=214 injuries	
Injured Area	Percent	Injured Area	Percent
Head	62.5	Thorax	42.5
Thorax	18.8	Head	41.1
Cervical Spine	12.5	General	6.1
		Abdomen	4.7
		Cervical Spine	3.7
Adapted from Coltman et al., 1989 (Reference 5)			

Fixed-wing aircraft mishaps produce the same general injury trends as do helicopter crashes: head and extremity injuries are the most prevalent. Injuries to the thorax occur less often in fixed-wing aircraft than in helicopter crashes. However, spinal injuries are more prevalent, particularly in land-based aircraft (Table 3).

Table 3. Injury rates from Naval fixed wing aircraft mishaps							
Land-based n = 14 injuries		Carrier-based n = 36 injuries		Training Aircraft n = 63 injuries		All aircraft n = 113 injuries	
Injured Area	Percent	Injured Area	Percent	Injured Area	Percent	Injured Area	Percent
Legs	28.6	Head	30.6	Head	28.6	Head	27.4
Spine	21.4	Arms	25.0	Legs	23.8	Legs	24.8
Neck	21.4	Legs	25.0	Neck	22.2	Arms	16.8
Head	14.3	Spine	11.1	Arms	12.7	Neck	15.0
Arms	14.3	Chest	8.3	Chest	7.9	Chest	7.1
				Thorax	3.2	Spine	7.1
				Spine	1.6	Thorax	1.8
Adapted from Coltman et al., 1988 (Reference 4)							

3.2 AIR FORCE MISHAP DATABASES

Injuries that occur in Air Force Class A mishaps were statistically determined from existing Air Force databases. Statistical summaries from three different database reviews are presented. First is a summary of Raddin et al.'s (Reference 6) review of the Air Force Safety Agency database of aircraft ejections from 1971 to approximately 1992; second is a summary of an Air Forces-generated ACES II seat-only database; and third is a summary of the Air Force Safety Agency Class A and B mishaps (including ejections and crash landings) database from 1971 to 1994.

3.2.1 Air Force Ejections, 1971 to 1992

Only serious injuries (e.g. fractures, sprains, strains, amputations, concussion, etc.) were tallied. Injuries were identified in two categories: (1) all mishaps and therefore, all injuries, and (2) mishaps where there were survivors and therefore, non-fatal injuries (Table 4).

Table 4.
Injury rates from Air Force ejections, 1971-1992

Air Force Ejections All injuries n = 688 injuries		Air Force Ejections Non-fatal injuries n = 367 injuries	
Injury	Percent	Injury	Percent
Thoracic spine fracture	18.5	Thoracic spine fracture	27.5
Head injury	12.7	Neck sprain/strain	17.7
Neck sprain/strain	9.5	Back sprain/strain	15.3
Back sprain/strain	8.1	Lumbar spine fracture	7.6
Rib fracture	6.4	Knee sprain/strain	4.1
Lumbar spine fracture	6.0	Head injury	3.5
Neck fracture	5.5	Shoulder sprain/strain	2.7
Extremity amputation	5.2	Ankle sprain/strain	2.7
Lower leg fracture	4.5	Upper arm fracture	2.5
Upper arm fracture	3.9	Shoulder fracture	2.5
Lower arm fracture	3.9	Thoracic spine sprain/strain	2.5
Upper leg fracture	2.8	Neck fracture	2.2
Shoulder fracture	2.3	Lumbar spine sprain/strain	2.2
Pelvis fracture	2.2		
Knee sprain/strain	2.2		
Adapted from Raddin, et al. (Reference 6). Remaining body segments have less than a 2 pct injury occurrence.			

In both categories, thoracic spine fracture was the most frequent injury to occur. While neck sprains and strains were also frequent, neck fracture was not a significant occurrence. One main difference between the injury categories was the decreased occurrence of head injury in the non-fatal injury situations.

From this database, a total of 38 cervical fractures were identified, 30 of which were associated with fatalities. The fatal neck injuries mostly occurred in the emergence, separation and chute deployment phases of the ejection sequence. Cervical fractures also occurred in the ejection phase, but these were less likely than the others to be fatal. Additionally, 70 pct of the neck sprains and strains were attributed to the forces endured during the ejection phase.

3.2.2 Air Force Ejections with ACES II Seats Only

A database containing injury information related to ejections with ACES II seats only has been tallied by the Air Force Safety Agency (Table 5). The injuries that occurred during ejections with ACES II seats are included in the mishap database summarized in Table 4 above. The most notable difference between the data sets (Tables 4 and 5) is the reduction in thoracic spine fractures from 18.5 pct for all ejections seats compared with 6.8 pct for ACES II ejections. The rate of lumbar spine fracture remained significant with the ACES II. However, the rate of cervical spine fracture decreased from 5.5 pct to 2.2 pct with the ACES II seat.

Table 5.
Injury rates from ejections from Air Force aircraft equipped with ACES II ejection seats.

Ejections with ACES II ejection seats, n=132 injuries

Injury	Percent
Neck sprain/strain	16.0
Multiple extreme injury (impact with ground)	10.6
Lumbar spine fracture	9.8
Back sprain/strain	7.6
Head injury	6.8
Thoracic spine fracture	6.8
Lower arm fracture	6.8
Thoracic spine sprain/strain	6.1
Lower leg fracture	6.1
Ankle sprain/strain	5.3
Shoulder fracture	3.0
Neck fracture	2.2
Upper arm fracture	2.2

3.2.3 Air Force Mishaps, Class A and B, 1971-1994

The database containing Air Force Class A and B mishaps from January 1971 to October 1994, which included the ejection-related mishaps summarized in Tables 4 and 5, was reviewed. The database was also reviewed prior to Simula's investigations of individual mishap records at the Air Force Safety Agency (Section 3.3). The database consisted of 3,919 mishaps, involving 6,434 people, 1,842 fatalities, and 12,345 injuries of all severity levels (up to 9 injuries were tallied per person). Only 201 people received no injury. The database revealed a total of 766 neck injuries, of which 232 were cervical spine injuries. Of the serious cervical spine injuries, 131 were cervical fractures, 24 were cervical sprains and strains (mostly at the C1 level), and 28 were dislocations (mostly at the atlantoaxial joint). 885 injuries were thoracic and lumbar spine fractures, 9 were lumbar spine dislocations (mostly at L1) and 28 were thoracic spine dislocations. Information from this database is included in the individual mishap database (Appendix A-1).

3.3 INDIVIDUAL AIR FORCE MISHAP FILES

A total of 64 individual mishap records were reviewed during a four-day visit to the Air Force Safety Agency. The records were pre-selected from a database of Air Force Class A and B mishaps (Section 3.2.3). The pre-selections were based upon body areas that were injured, the severity of the injury, and upon the year the mishap occurred. The four body areas of interest included the head, the cervical spine, the thoracic and lumbar spine, and the extremities. Injury severity was pre-selected by searching for serious injuries - bony fractures, dislocations and sprains/strains. Priority was given to the most recent mishaps. The search strategies used can be summarized as follows (in order of priority):

1. Four body areas, serious injuries, 1990-October 1994.
2. Four body areas, serious injuries, 1986-1989.
3. Survived serious neck injuries, 1980-1985.

Approximately one-third of the requested files, particularly the most recent files, were unavailable for review.[1] In the individual mishap files reviewed, most of the serious neck and spine injuries from the first two search categories were cases of multiple extreme injury. These multiple extreme injuries typically occurred during impact with the ground or with the cockpit structure. These situations did not provide much useful information for determining injury tolerances, since the loading incurred by the individuals was well beyond the limits of human tolerance. The final search category was initiated on the hopes of locating survived neck fractures.

The mishap files are extensive. However, since individual occupant reconstructions were not performed, data about the loads and accelerations experienced by the individual were not available. The Life Science Report was the most informative section of each mishap file. Specific information regarding the injuries was collected and identified in this report. The Life Science Report and reported interviews with the crew members and mishap witnesses together provided information about the cause of the injury or the phase of the ejection sequence where the injury occurred. Aircraft velocities, attitudes, and altitudes at the time of ejection or mishap were also collected. All of the information gathered from the mishap files was combined with the information from the Air Force database (Section 3.2.3) to form one database with complete information on the 64 mishaps (Appendix A-1). Textual summaries of each mishap scenario are collected in Appendix A-2.

Of the 64 mishap files reviewed, 34 mishaps resulted in a total of 143 crew fatalities. There were no fatalities in the remaining 30 mishaps. The cause of the fatalities can be divided into four categories (Table 6).

[1] Files were checked out of the library. During busy weeks, almost half of the most recent files are usually checked out.

Table 6. Fatalities in Individual Mishaps from Air Force Safety Agency records				
Category	Description	Mishaps	Fatalities	Survivors
1	Crash landings, ditchings, controlled flight into ground	19	123	12
2	Out-of-envelope ejections	9	12	9
3	Mid-air collisions	3	4	4
4	Ejection system failure	3	4	1
	Total	34	143	26

The high number of fatalities from crash landings was due to the type of aircraft involved in these situations. For example, many were transport aircraft without ejection seats: HH-60G with 12 fatalities, C-130B with 5 crew fatalities, and the C-130E with 6 fatalities. In the out-of-envelope ejection category, the most striking observation came from the four mishaps in which the person in the rear seat ejected safely, while the front seat occupant was killed on ground impact with insufficient time for chute deployment. The even split in fatalities and survivors from mid-air collisions relates to the entire crew in one aircraft being killed while the entire crew in the second aircraft survived.

A summary of neck and spinal injuries identified from the 64 individual mishaps reveals several trends. (Note that the number of files is small and was biased by our selection process). These trends include the following:

- Of a total of 9 survived neck injuries there was 1 cervical fracture (C2), 6 cases of sprain/strain, and 2 cases of cervical stiffness. The causes of these injuries were difficult to discern, as the injury was not noticed by the injured individual until after the completion of the rescue. Fatal neck injuries were not tallied in this manner.
- Fractures to the thoracic and lumbar spine were more common than neck fractures, with 29 persons suffering a total of 42 thoracic or lumbar spinal fractures compared to one cervical spine fracture.
- The thoracic and lumbar spinal fractures were mostly classified as compression fractures (25 fractures) and wedge fractures (10 fractures). Burst fractures, transverse process fractures, and spinous process fractures were also identified.
- Of the 10 wedge fractures, 7 were classified as anterior wedge fractures, implying a combined compression-flexion loading to the vertebrae.
- Only 3 cases of thoracic/lumbar sprain or strain were noted.
- The position of the head and torso during ejection seemed to affect the occurrence of spinal injury. However, since determining the head and body location prior to ejection was based on the crew's recollection, the degree of eccentricity of the load was difficult to ascertain.
- Spinal compression fractures did occur as a result of parachute landing force. These fractures were the result of a primarily compressive load applied to the spine through the pelvis.
- The crew did not often recall the exact moment of spinal injury. Therefore, the phase of injury occurrence is often determined after the injury itself is identified. For example,

wedge and general compression fractures were often associated with the ejection force, parachute landing force, and chute opening shock.

- Compression with an eccentric load is a primary mode of failure in the cervical, thoracic and lumbar vertebrae. These fractures, sprains, and strains were most often associated with ejection force, parachute landing force, and chute opening shock.

Several overall observations were made that may contribute to the determination of the injury criteria:

- Age, level of fitness, and previous injury may affect the occurrence and severity of the injury.
- Many of the Class A situations were not survivable. A return to the files to review Class B mishaps and survived Class A mishaps may prove valuable to the development of a comprehensive understanding of the mishap environment.
- A quantitative relationship between the loading suffered during the scenario and the injury produced by the scenario is difficult or impossible to determine from the information collected in the mishap records. However, a conceptual understanding of the injury-causing scenarios was formed.

3.4 NECK INJURY SCENARIOS IN THE GENERAL POPULATION

Cervical spine injuries that occur to the general population were identified from the literature. A variety of circumstances were determined to be the cause of cervical spine injuries. Neck injuries can lead to permanent disability or fatality. As was shown in Section 3.2 and 3.3, neck injury occurs regularly in the aircraft environment. However, the main cause of cervical spinal cord injury in the general population is from automobile accidents (Table 7). A total of 7,250 new cases of transport-related cervical spine injuries are reported annually, 75 pct of which are fatal at the scene of the accident (Reference 7).

Table 7.
Activities Associated with Ceervical Spinal Cord Injury

Activity	Percent of Cases
Automobile Accidents	36.5
Fall	15.8
Gunshot wound	11.6
Shallow water diving	10.6
Motorcycle accident	6.2
Hit by falling/flying object	5.4

Based on a total of 2,304 reported cases. Adapted from Myers et al. (Reference 25), as reported from the National Spinal Cord Injury Data Research Center.

Cervical spine injury can be devastating, often leading to permanent disability if the injury is survived. Yoganandan, et al. (Reference 9) performed a retrospective study of 347 patients admitted to the hospital following cervical injury, with 38 pct of the injuries from motor vehicle accidents. The patients were divided into three groups based on the extent of neurological damage suffered. Of these patients, 30 pct suffered from complete quadriplegia, 30 pct from incomplete quadriplegia, and 40 pct showed no neurological deficit. Those involved in motor vehicle accidents showed a similar breakdown in injury severity. The most common injury mechanisms for the complete and incomplete quadriplegics were compression-flexion and pure axial compression, with the injuries predominant in the lower cervical spine. In the cases with no neurological deficit, flexion-rotation was also a significant injury mode, with 80 pct of the injuries occurring between C4 and C7. Children and infants are particularly vulnerable to spinal cord injury. The enlarged head, in proportion to the supporting neck structure, provides for a greater chance of inertial injuries, with injuries particularly occurring in the upper cervical spine (Reference 10).

3.5 INCORPORATING THE DATA INTO AN INJURY CRITERION

The data collected from the Air Force databases and mishap files provide a firm conceptual basis for the injury scenarios commonly encountered. For example, axial compression seems to be a major mode of failure in both military and civilian spinal fractures. However, the lack of information in these files regarding loads and accelerations experienced by the individuals in the mishaps prevents direct application of the data into an injury criterion. Injury mechanisms and loads have to be determined separately through a thorough analysis of the literature. Section 4.0 describes how the loads were determined for specific injuries. Section 5.0 then details the development of the axial compression branch of the neck injury criterion, using the data from Sections 3.0 and 4.0.

4.0 TASK 2 - DETERMINE MECHANISMS AND LOADS RELATED TO NECK INJURY

The goal of Task 2 was to determine the mechanisms and loads related to neck injuries through a literature review. This section provides a description of the human neck anatomy to inform the reader of the basic terminology used in the remaining sections (Section 4.1). The basic injury mechanisms for the cervical spine are presented (Section 4.2), and the loads and accelerations that lead to injury are summarized (Section 4.3). Finally, incorporating this information into the injury criterion structure is discussed (Section 4.4).

4.1 ANATOMY

The purpose of this anatomical background is to provide a general overview of the anatomy of the cervical spine and the individual vertebral bodies. The cervical spine consists of seven cervical vertebrae (Figure 2). The most superior vertebra is designated as C1 and the most inferior is designated as C7. The C1 vertebra is also known as the atlas and the C2 vertebra is also known as the axis. The atlas is a bony ring with no defined vertebral body. Enlarged facets on the atlas allow for articulation with the base of the skull. The axis has a bony projection called the dens, or odontoid process, which projects upwards and serves as the vertebral body of the atlas. The dens also serves as the axis about which the head and atlas rotate. The joint between the base of the skull and the C1 vertebra is the occipitoatlantal joint. The joint between the first and second cervical vertebrae is the atlantoaxial joint.

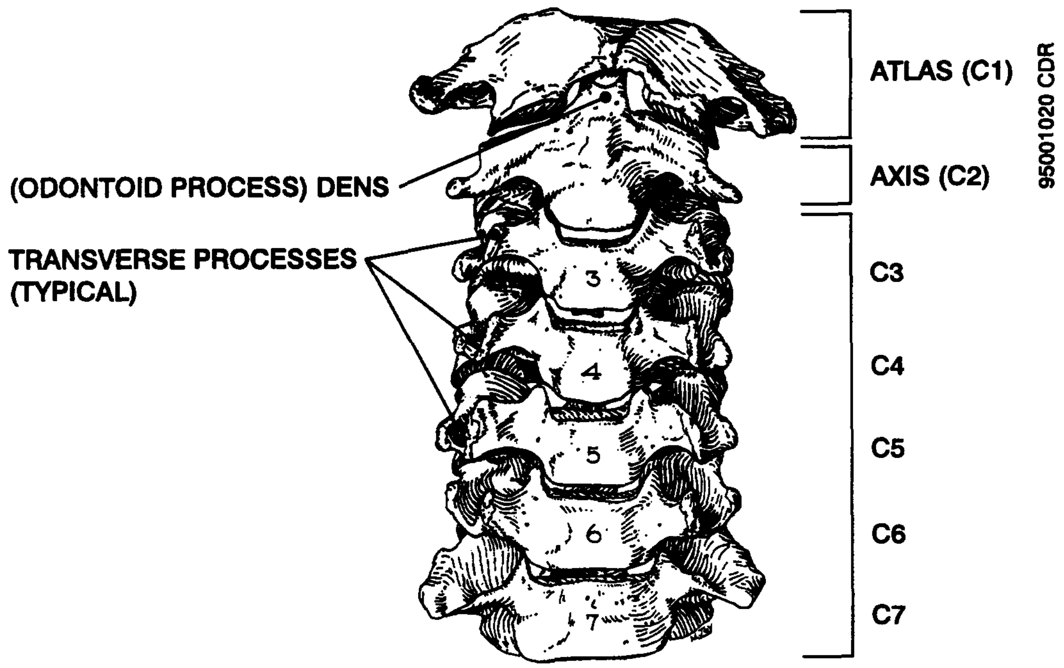
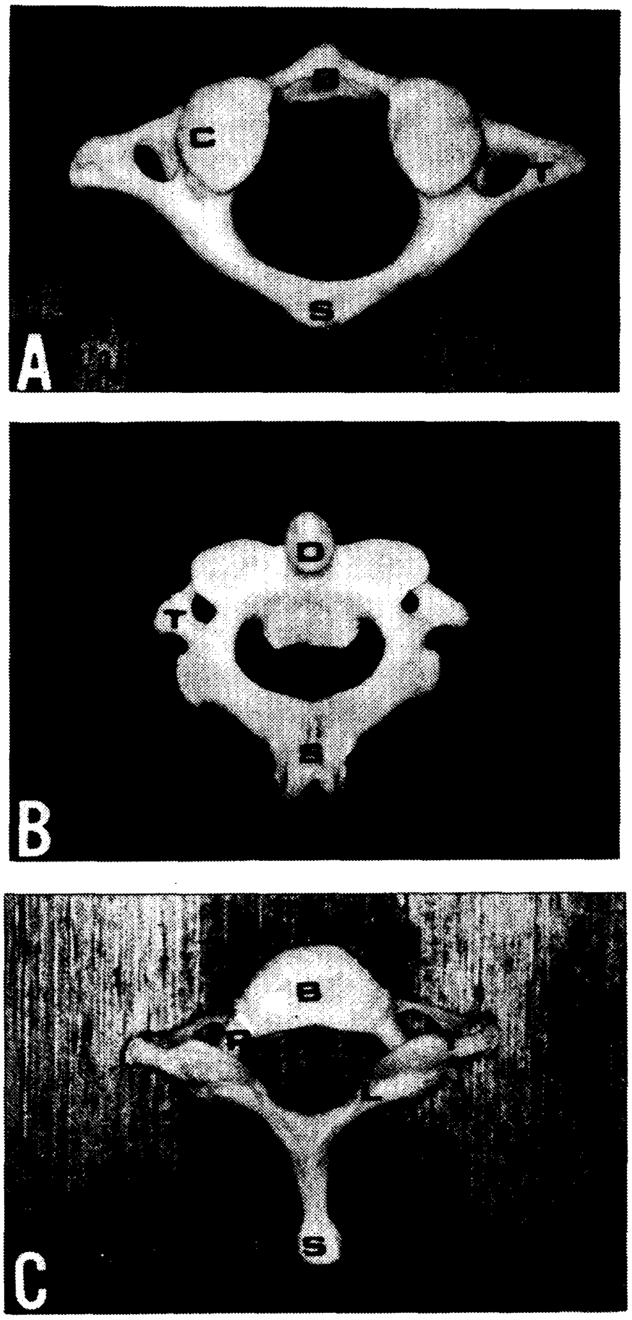


Figure 2.
The cervical spinal column. Adapted from McElhaney and Myers (Reference 8).

From C3 to C7, the vertebrae are similar geometrically. The size of the vertebrae increases from the superior (C3) to the inferior (C7). Each of these vertebrae has a cylindrical vertebral body connected to various bony elements (Figure 3). These elements include the pedicles, lamina, spinous processes, transverse processes, and the superior and inferior facets. The structure formed by these elements is collectively referred to as the vertebral or neural arch. Facets, found on both the superior and inferior sides of the vertebrae, are flattened surfaces which provide an area for articulation with the neighboring vertebrae.



B = VERTEBRAL BODY
C = CONDYLE OR FACET
S = SPINOUS PROCESS
T = TRANSVERSE PROCESS
D = DENS
P = PEDICLE
L = LAMINA

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Figure 3.
Individual cervical vertebrae. (a) C1, the atlas. (b) C2, the axis. (c) C7, geometrically representative of each of the C3 to C7 vertebrae (Reference 11).

A number of ligaments hold the vertebral bodies together. These ligaments include the anterior and posterior longitudinal ligaments, which span the anterior and posterior portions of the vertebral bodies, and ligaments generally named for the parts that they connect, including the intertransverse ligaments which connect the transverse processes, the interspinous and supraspinous ligaments which connect the spinous processes, and the ligament flava which connect adjacent lamina. The vertebral bodies are connected to each other by means of an intervertebral disk. The disk is a fibrocartilaginous structure composed of a central nucleus pulposus and surrounded by the annulus fibrosus, a laminar set of fibrous sheets.

Motion of the neck can be defined as the global movement of the head relative to the torso. For example, flexion, extension, bending, and rotation, as shown in Figure 4A. Loading of the individual vertebrae is described in similar terms. However, the individual vertebral loads may or may not relate to the global motion descriptions. Example of loading descriptions include bending, compresion, tension, rotation, and shear (Figure 4B).

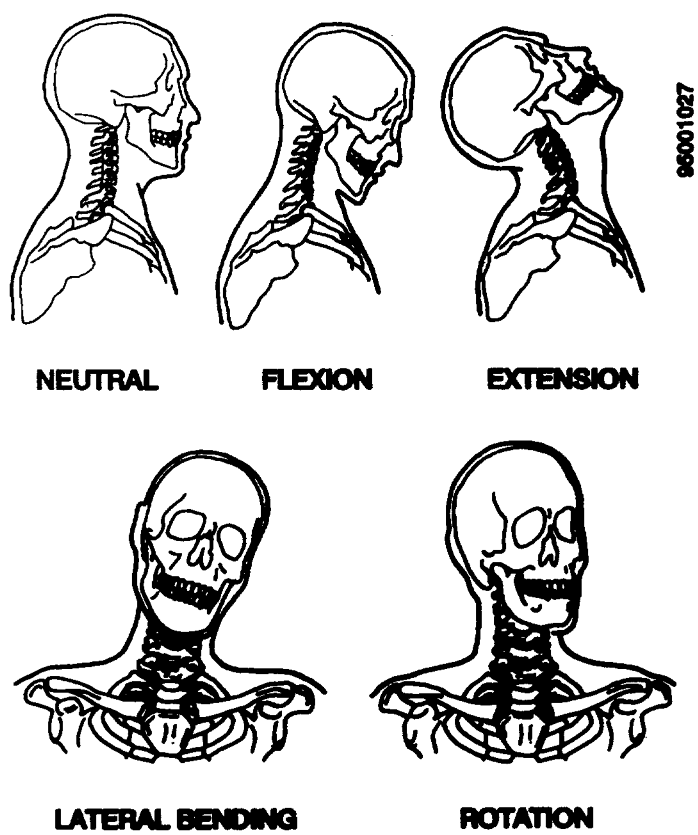


Figure 4a.
Global motions of the neck.

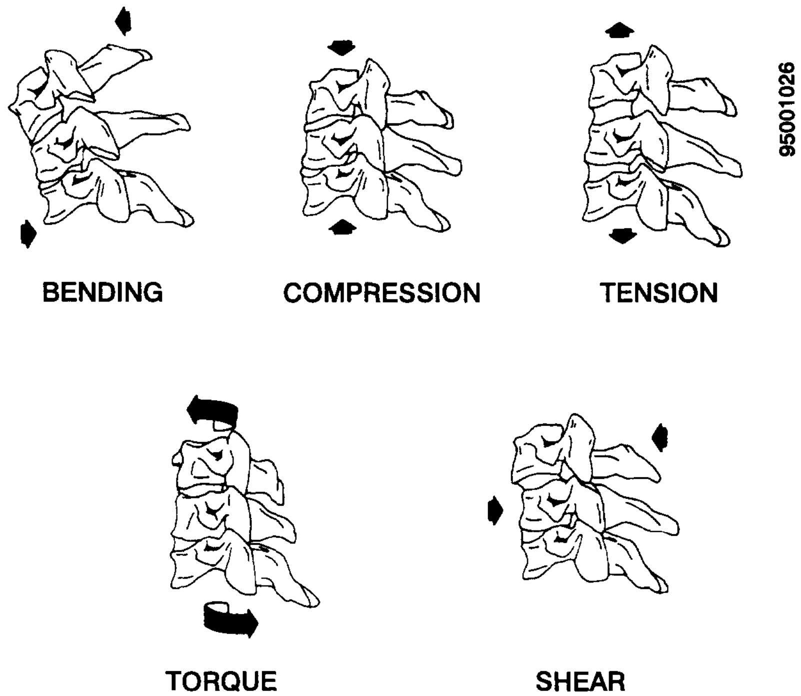


Figure 4b.
Vertebral body loading directions.

4.2 INJURY MECHANISMS

This section details the relevant mechanisms for injury at the neck. Relevant injuries are primarily bony fractures, dislocations, and serious soft tissue injuries. Cervical injury mechanisms are classified according to the motion of the neck that may have occurred to cause injury. However, neck motion, as defined by the relative motion of the head to the torso, may not be the same motion that occurs to a functional spinal unit (two vertebrae and their associated intervertebral disk) where the injury actually occurs. Therefore, neck injury classifications are defined in terms of loading at the functional spinal unit. This classification system can be used to test whole cadavers as well as cervical sections. Neck motion can be classified into seven primary and four common combined (for a total of 11) motion directions. The classification scheme is adapted from McElhaney and Myers (Reference 8). For each of the 11 different neck injury classification directions, there are 1 to 6 injury mechanisms. Appendix B contains a database with detailed descriptions of the injury mechanisms.

1. Axial Compression

- Ligamentous injury
- Jefferson fracture
- Multipart axis fracture
- "Compression fracture"
- Burst fracture

2. Axial Tension

- Occipitoatlantal dislocation

3. Flexion
- Hyperflexive strain
- Facet dislocations
- Teardrop fracture
- Fracture of dens and spinous processes
- Wedge fracture
- Coal shoveler's fracture

4. Extension
- Hyperextensive strain/dislocation
- Anterior longitudinal ligament tear
- C2 fracture of the pedicles
- Hangman's fracture
- Avulsion fracture
- Teardrop fracture of axis

5. Horizontal Shear
- Transverse ligament rupture
- Odontoid fracture

6. Rotation
- Atlantoaxial dislocation

7. Lateral Bending
- Unilateral locked facets
- Transverse process fracture
- Nerve root avulsion
- Lateral wedge fracture

8. Compression - Extension
- Posterior element fracture
- Fracture-dislocations

9. Compression - Flexion
- Hyperflexive strain
- Uni- and bi-lateral dislocations
- Wedge fracture
- Teardrop fracture
- Burst fracture
- Fracture dislocation

10. Tension - Extension
- "Whiplash"
- Anterior longitudinal ligament tear
- Intervertebral disk rupture
- Horizontal vertebral body fracture
- Hangman's fracture
- Teardrop fracture

11. Tension - Flexion
- Bi-lateral facet dislocation

4.3 INJURY LOADS

This section identifies experimental studies from the literature that determined injury-producing loads. The loads that cause injuries were related to the injury locations and mechanisms to form the neck injury criterion. To develop the appropriate relationships, data were collected from experimental and medical literature and was stored in a database. Appendix C represents this database, which details the injury-producing loads. From the database, the literature data were sorted by loading scenario and were compared to each other. A subjective evaluation of data available for each scenario was made and injury tolerance levels were determined.

Several challenges were encountered while comparing the results of various experiments to determine the appropriate injury tolerance level. Specifically, different conditions made the experimental results difficult to compare. Four considerations were made while comparing the data. First, the types of specimens used for testing vary with the testing protocol. For example, some tests used whole cadavers (e.g., Alem, et al., Reference 12; Nightingale, et al., Reference 13), other tests used the whole cervical spine (e.g., Bauze and Ardran, Reference 14; Maiman, et al., Reference 3) or isolated functional spinal units (e.g., Liu, et al., Reference 15; Moroney, et al., Reference 16). Some mechanical tests have also been performed on single vertebrae (e.g., Yamada, Reference 17) or on live volunteers (e.g., Mertz and Patrick, Reference 18).

A second consideration in comparing the experimental studies was the rate at which loading was applied to the subject. Most of the testing that has been performed was in the quasi-static range. The relationship of the quasi-static data to dynamic and impulse environments is not well understood. The rate-dependent effects may lead to higher measured peak forces and to different types of injury mechanisms.

A third consideration was the inherent differences among individuals within a study or between studies. For example, in the isolated vertebral disk, the compressive strength of the disk is decreased over 50 percent in those who are aged 60 to 79 as compared to 20- to 39-year-olds (Reference 17). Additionally, the degree of constraint placed upon the test specimen may be significant in terms of the tolerance to injury and upon the injuries produced. For example, when the head is constrained and the neck is required to stop the movement of the torso, the incidence of injury may be increased (Reference 19).

Finally, in specific relation to building the neck injury criterion, the complexity of the cervical spine structure may have caused small differences in the loading protocol of the tests to produce large differences in experimental results. This effect was demonstrated by the sensitivity of the results to slight changes in loading patterns. For example, McElhaney et al. (Reference 20) showed that only 1 cm of eccentric loading changed the injury mechanisms seen in the isolated cervical spine from pure compression to compression-flexion or compression-extension, thereby changing the injury type and level of injury tolerance.

4.4 INCORPORATING THE DATA INTO AN INJURY CRITERION

The information collected from the literature was incorporated into the neck injury criterion to the greatest extent possible. The injury criterion structure, as described in Section 5.0, required loading information as input data, produced injury information as output data, and consisted of a correlation of these data with injury tolerances. Information on anatomical and injury mechanisms was used to develop the injury criterion outputs. Whenever possible, specific injury mechanisms and their related anatomical information was included in the output. Future development of the criteria into a software format will allow for graphical representation of the exact anatomical locations that may be affected by a loading scenario.

The injury mechanism descriptions and the experimental data were related to develop the injury tolerances. The most common injury mechanisms were determined from the injury scenarios reviewed. The criteria were ultimately limited by the amount of information available from the experimental literature regardless of which injuries were most common. The quantified injury criterion for axial compression of the cervical spine is presented in Section 5.0. The individual assumptions necessary to develop tolerances for each scenario are presented in that section.

Several general strategies were used to deal with incorporating the experimental data into a neck injury criterion. The strategies particular to the development of the neck injury criterion are described in accordance with the four considerations discussed in Section 4.3.

First, whole cadaver and live volunteer data were used to determine the neck injury criterion when possible. However, data produced from cadaver tests and live volunteer tests are conservative measurements. The cadaver measurements are conservative since the effect of active musculature is not accounted for. Also, since many of the cadavers are elderly, there is an increased likelihood of decreased bone strength. The live volunteer data is also conservative since testing loads fall short of producing serious injury. Additionally, if a soft-tissue injury was produced, the injury could not be quantified. Soft-tissue injuries, such as sprains and strains, cannot be quantifiably diagnosed externally and invasive measures cannot be performed to determine the anatomical significance of effective injuries. When experiments utilizing whole cadaver or volunteer data were not available, isolated whole spine experiments were used for criteria development.

Second, the criterion structure accounted for loading rate variations by differentiating between static/quasi-static and dynamic/impulse testing. The loading rate of 15 ft/sec (approximately 10 mph) was arbitrarily chosen to separate experimental procedures into these two defined groups. There was not always sufficient loading rate information in the experimental data to fully quantify the criteria for each of these loading situations. Nevertheless, the criterion structure was developed so as to accommodate this distinction between static/quasi-static and dynamic/impulse when future experimentation provides sufficient data.

Third, the inherent differences in individuals (amongst human volunteers and amongst cadavers) were accommodated by including two separate categories: average and vulnerable individuals. In circumstances when a minimum tolerance for injury was reported, that value is used as the tolerance for the vulnerable individual. Otherwise, a value of one to two standard deviations from the average tolerance values is used. The average tolerance values are generally the average of the subject population utilized in the study. This value is conservative, since much of the testing was already inherently conservative and since many of the cadavers used fit into the vulnerable category. Nevertheless, adjusting the values based on an estimate of the relationship of the study population to the general population was not appropriate at the time of criterion development.

The fourth consideration addressed in Section 4.3 was specific to the cervical spine. The complexity of the cervical spine was taken into consideration when designing the neck criterion structure, particularly in determining the specific scenarios to be quantified. For example, axial compression of the spine was categorized into four secondary loading possibilities: pure compression, compression-flexion, compression-extension, and compression with eccentricity. The compression with eccentricity category was created to demonstrate the decreased tolerance to force with off-axis loading, regardless of the direction of eccentricity. Compression-flexion and compression-extension are common occurrences, warranting their own categories.

5.0 TASK 3 - FORM INJURY CRITERION STRUCTURE AND NECK INJURY CRITERION

Several of the challenges to developing the injury criterion structure and the neck injury criterion were discussed in Sections 3.5 and 4.4. These sections addressed the incorporation of the scenario data and the literature data into the injury criterion. The following sections present detailed descriptions of the injury criterion structure (Section 5.1) and the quantified neck injury criterion for axial compression (Section 5.2). Also included in this section is a comparison of the branched neck injury criterion developed by Simula to the neck injury criteria developed by others (Section 5.3).

5.1 INJURY CRITERION STRUCTURE

The injury criterion structure developed in this Phase I effort determines human-based injury outputs using human-based loading inputs. The inputs are load direction, direction of off-axis loading, load magnitude, load rate/duration, and subject condition (Figure 5). The criterion outputs are injury mechanism, injury location, injury severity, and the experimental references used to determine these outputs. A description of each component of the criterion (input, output, structure) follows. The injury criterion structure is demonstrated through the neck injury criterion.

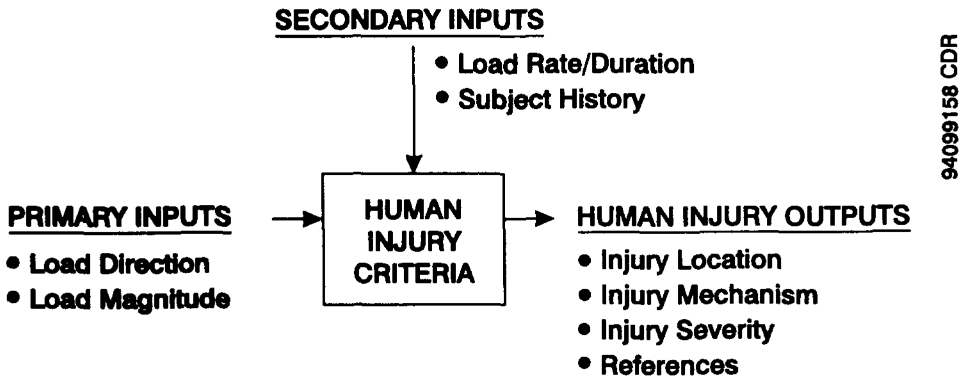


Figure 5.
Schematic of Human Injury Criterion Structure.

5.1.1 Injury Criterion Inputs

Primary Loading Directions: Compression, Tension, Flexion, Extension, Rotation, Lateral Bending, or Horizontal Shear. These seven primary loading directions also correlate to seven of the eleven injury mechanism categories.

Off-axis Loading: Compression-extension, Compression-flexion, Tension-extension, Tension-flexion. Directions are dependent upon the input primary loading direction. Combined loading could include any of the primary loading directions. The four examples correlate to the four combined injury mechanism categories.

Loading Rate/Duration: Static/quasi-static or Dynamic/impulse.
Static/quasi-static and dynamic/impulse loading rate/duration were differentiated on the basis of experimentation suggesting that load rate/duration may be a parameter in determining the injury mechanism. Experimentation by Alem, et al., (Reference 12) concluded that impulse (the relationship of peak force and load duration) may provide the best means to predict the injury mechanism.

Subject Factors: Average or Vulnerable.
A vulnerable person is one who is over age 50; of extreme stature (e.g. obese or very small); has skeletal abnormalities (e.g., scoliosis) or bone or joint degeneration; or has had a prior injury to the body area.

Loading Magnitude: Two or more load limits or ranges will be presented. The specific magnitudes and number of choices will depend upon the scenario being described. In combined loading situations, two choices of magnitude may be made; for example, force and bending moment may both be loading magnitude inputs. The load magnitudes presented form the injury tolerances for the specific loading scenario.

5.1.2 Injury Criterion Outputs

Injury Mechanism: None, Sprain/strain, Fracture, Fracture/dislocation.
The injury mechanisms will be specific to the body area and loading direction. These mechanisms are defined in Appendix B.

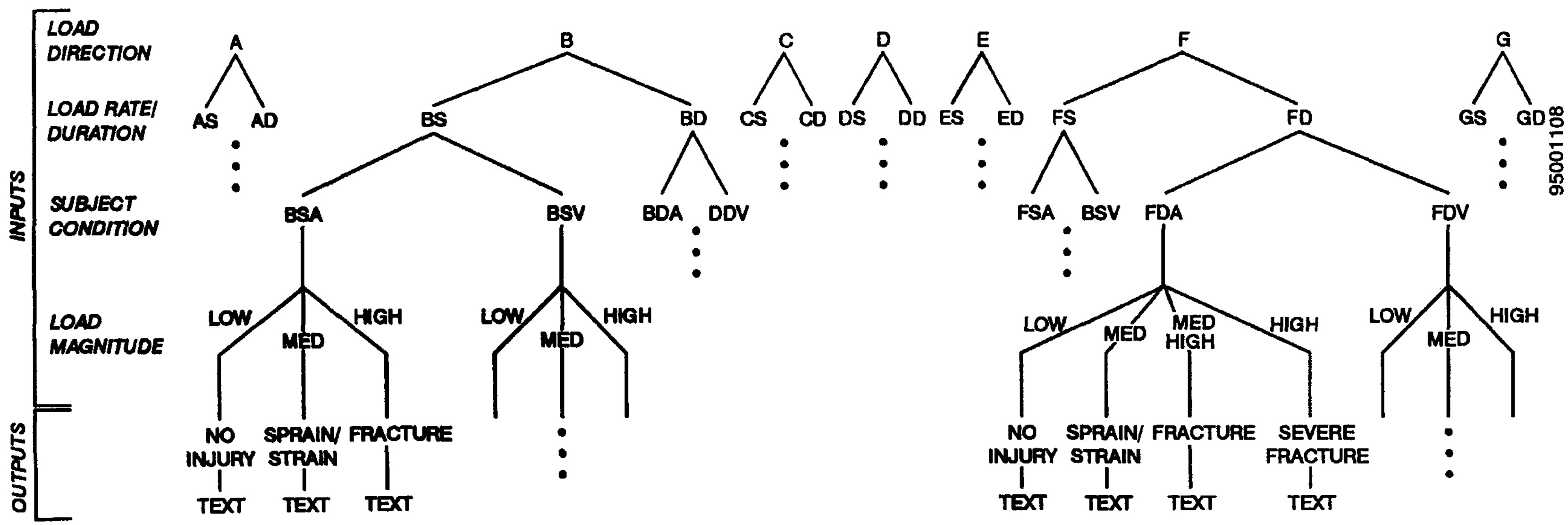
Injury Severity: None, Minor, Major, Severe, Fatal.
Minor injuries are soft-tissue injuries that require little or no convalescence. All fractures are at least major injuries. A severe injury requires extensive recovery and may involve permanent or neurological damage. A fatal injury is defined as the injury that may have caused the fatality. No attempt was made to assign Abbreviated Injury Scale (AIS) ratings to the injuries.

Injury Location: The injury location will be presented in as much detail as possible. For example, a specific cervical vertebra (e.g. C4-C6, C2) or a specific location on the vertebra (e.g. vertebral body, spinous process).

References: The experimental literature used to determine the tolerance level will be referenced.

5.1.3 Injury Criterion Structure

The injury criterion is a branched structure, with each input providing an additional level of branching (Figure 6). An individual branch relates a set of inputs to a set of outputs. First, the primary loading direction is input, followed by the off-axis loading, the loading rate, and the subject condition. The final step of data input is the selection of the appropriate magnitude range. Quantification of the magnitude ranges and their relationship to injury types is based upon the experimental literature (see Section 4.3, Appendix C). Once the magnitude range is specified, the outputs are determined. Currently, the outputs are in textual blocks that describe the injury mechanism, injury severity, injury location and the references used to determine these outcomes.



A - G = Primary loading conditions. For simplicity, off-axis loading is not shown.
S = Static/quasi-static load rate/duration
D = Dynamic/impluse load rate/duration
A = Average subject condition
V = Vulnerable subject condition
TEXT - Information on the injury, location, injury severity, and the references used to determine the criteria.

Figure 6.
Branched injury assessment criterion structure.

Available experimental data have been insufficient to completely quantify the criterion to the level of detail set up in the criterion structure. The criterion structure has been developed to accommodate new data as new experimentation is performed. However, until new data are available, the input sets for which there are no experimentally defined outputs will lead to the most appropriate outputs. Specifically, for the axial compression branches of the neck injury criterion, distinct tolerances for vulnerable individuals and for dynamic/impulse situations were not always available. In these circumstances, the tolerances for average individuals or static/quasi-static situations were used.

Most soft-tissue injuries were not incorporated into the criterion. The main reason for this exclusion is that cervical soft tissue injuries, such as sprains and strains, are poorly defined and understood. Soft-tissue damage is also hard to quantify. Not only is soft-tissue deformation very rate-dependent, but this rate-dependency and the degree of elasticity both change with the increase in collagen content as a person ages. Even when soft-tissue can be tested through the plastic range, the relationship of mechanical failure to clinical sprains and strains is not well understood.

Additionally, when dealing with an injury criterion for the neck, it is important to note that this criterion focuses primarily on fractures, dislocations, and ligament tears. The lack of injury to these structures should not imply that there is no chance of a fatality or injury to other structures as a result of other types of injuries. For example, a direct impact to the neck is only considered in relation to the vertebral fractures and dislocations that may be produced from horizontal shear loading. In addition to these injuries, there is a danger of injury to the airway and the circulatory system. Damages to each of these systems is potentially life-threatening and may occur before bony fracture. Prediction of airway damage and other such injuries (e.g., lacerations) are beyond the scope of this criterion.

5.2 NECK INJURY CRITERION - AXIAL COMPRESSION

One section of the neck injury criterion (axial compression) has been fully quantified. The axial compression branch was selected for development since it is the primary direction of spinal injury (see Section 3.3 and 3.4) and because it has been the most thoroughly studied neck injury mode in the experimental literature. Four different directional sub-conditions of axial loading were considered (Figure 7):

1) Pure axial compression
2) Compression with flexion
3) Compression with extension
4) Compression with eccentricity.

Loading must be more than 5 deg off-axis to be considered a combined loading scenario. Compression with flexion and compression with extension are common combined loading scenarios. For example, these combined loading scenarios are encountered in ejection situations when the head is bent forward (compression-flexion) or backwards (compression-extension) as the torso is projected upwards. The "compression with eccentricity" category was developed to provide a more general expression for the decrease in the compressive strength when an off-axis loading component is present. Examples of additional eccentric loads that may fall into this category include lateral bending and rotation.

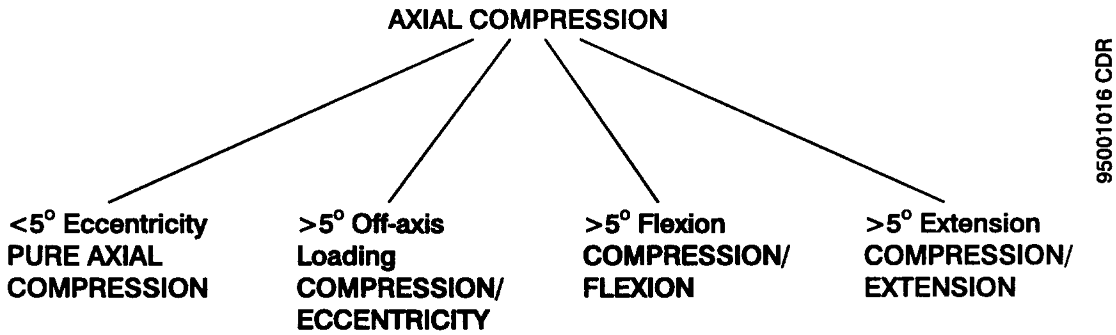


Figure 7.
Directional options for the axial compression branch of the neck injury criterion.

Details of the injury tolerances for each of the four directional subdivisions are presented in the following section. For pure axial loading and axial compression with eccentricity, the force tolerances are detailed. For compression with flexion and compression with extension, tolerances are expressed as compressive forces and bending moments. Details of how each directional criterion was set up and the rationale for choosing each tolerance level are described in Sections 5.2.1 to 5.2.4. There are four general outcomes or branches for each of the axial compression directional branches:

1) Static/quasi-static loading for average individuals
2) Static/quasi-static loading for vulnerable individuals
3) Dynamic/impulse loading for average individuals
4) Dynamic/impulse loading for vulnerable individuals.

When there was not enough data available to fully quantify the data for each specific category, tolerance values for the most closely related scenario(s) were used. Each of the following sections explains if the data used to predict injury is specific to that section or if it is an adaptation from a different data set.

5.2.1 Pure Axial Compression of the Cervical Spine

Pure axial compression of the spine occurs most often when a load is applied through the head to an aligned neck and spine. Pure axial compression seldom occurs in the real world. The tolerance levels are presented as force tolerances since more than minimal moments would necessitate the use of a combined loading description. Figure 8 details the pure axial compression branch of the neck injury criterion. Table 8 lists a description of the anticipated injuries corresponding to the numbers circled at the end of each branched loading criterion. To use the injury criterion, one must first obtain some information on an applied load. For example, if an ejection seat were tested with a Hybrid III manikin, forces and movements would be measured at the six-axis Denton load cell which is located at the interface between the head and neck. Films of the test could be used to determine the most likely response of the neck. In this example, axial compression is selected. Since the ejection seat test was conducted under dynamic conditions, the dynamic/impulse branch is selected. Healthy military personnel are the most likely to use the ejection seat; therefore, the "average" category is the selected on the "subject condition" branch. If the Z direction forces (i.e., compressive forces) measured in the six-axis load cell are less than 1,080 lb, then the predicted injury corresponding to 1 (Figure 8) is described in Table 8, the figure legend. If the axial compression force is between 1,080 - 1,350 lb, then the most likely injury(ies) to occur

are those described in Table 8 under 5. The injury outcome is based on how the branches above
the output level are selected. If the load rate appears to be less than 15 ft/sec, then the static/quasi-static branch should be selected. The subject factor is selected on the basis of the anticipated user of the device undergoing evaluation. For example, if the user is over 50, of extreme stature (e.g., obese or very small), has skeletal abnormalities (e.g., scoliosis), or bone or joint degeneration; or has had a prior injury to the body area, then the "vulnerable" branch may be selected.

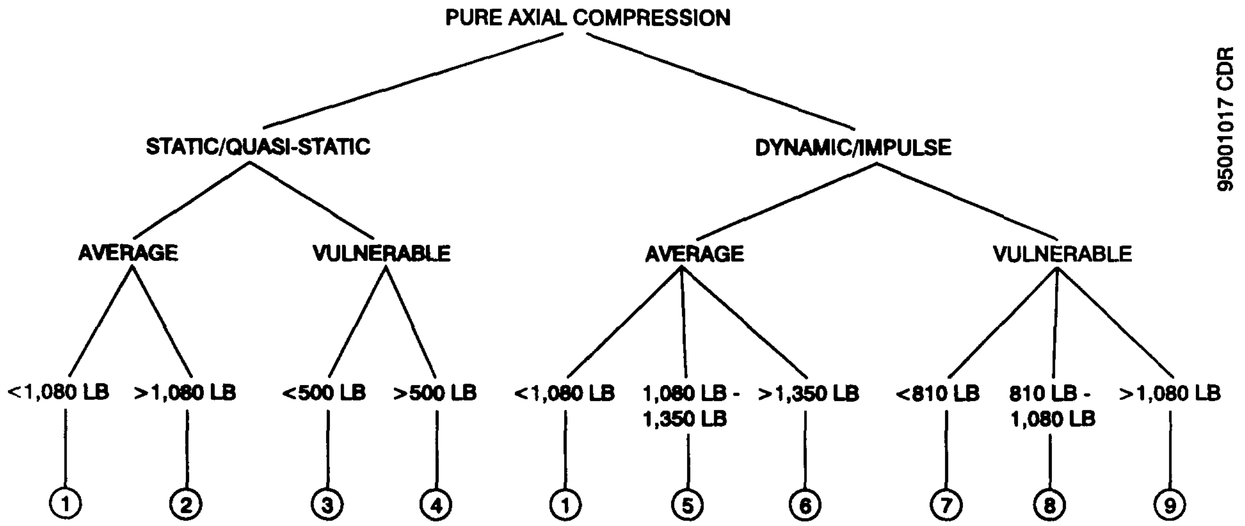


Figure 8.
Injury criterion for pure axial compression loading of the cervical spine.

Table 8.	
Legend for Figure 8. Injury criterion for pure axial compression loading of the cervical spine.	
1.	Injury expected: None Based on Nightingale, et al. Reference 13).
2.	Injury expected: Compression fractures (burst, Jefferson, multipart axis, and general loss of vertebral body height) Injury location: All possible, most likely lower cervical vertebrae (C4 to C6) Injury severity: Major to Fatal Based on Nightingale, et al., (Reference 13).
3.	Injury expected: None Based on Maiman, et al. (Reference 3), and Nightingale, et al. (Reference 13).
4.	Injury expected: Compression fractures (burst, Jefferson, multipart axis, and general loss of vertebral body height) Injury location: All possible, most likely lower cervical vertebrae (C4 to C6) Injury severity: Major to Fatal Based on one standard deviation from average of Maiman, et al. (Reference 3) and two standard deviations from average of Nightingale, et al. (Reference 13).
5.	Injury expected: Compression fractures (burst, Jefferson, multipart axis, and general loss of vertebral body height) Injury location: All possible, most likely lower cervical vertebrae (C4 to C6) Injury severity: Major to Fatal Based on Nightingale, et al. (Reference 13) and Alem, et al. (Reference 12).
6.	Injury expected: Severe compression fracture. High chance of general compression fracture (burst, Jefferson, multipart axis, and general loss of vertebral height) Injury location: All possible, most likely lower cervical vertebrae (C4 to C6) Injury severity: Major to Fatal Based on Alem, et al. (Reference 12)
7.	Injury expected: None Based on Culver, et al. (Reference 21)
8.	Injury expected: Compression fractures (burst, Jefferson, multipart axis, and general loss of vertebral body height) Injury location: All possible, most likely lower cervical vertebrae (C4 to C6) Injury severity: Major to Fatal Based on Culver, et al. (Reference 21) and Nightingale et al. (Reference 13).
9.	Injury expected: Severe compression fracture. High chance of general compression fracture (burst, Jefferson, multipart axis, and general loss of vertebral body height) Injury location: All possible, most likely lower cervical vertebrae (C4 to C6) Injury severity: Major to Fatal Based on Nightingale, et al. (Reference 13).

5.2.1.1 Static/quasi-static Loading in Average Individuals

For static/quasi-static loading in average subjects, the tolerance for injury was based upon the experimental work of Nightingale, et al. (Reference 13). Pure axial load magnitudes over 1,080 lb are likely to cause significant injury and magnitudes under 1,080 lb are unlikely to cause injury. The injuries expected to occur when the loading tolerances are exceeded are compression fractures and burst fractures. The general term "compression fracture" encompasses the specific injury mechanisms of a Jefferson fracture (C2 fracture), a multipart axis fracture (C1 fracture), and a loss of vertebral body height. These fractures range in severity from major to fatal with most general fractures occurring to the C4 to C6 vertebrae. The burst fracture is particularly likely to cause neurological damage, as bony particles impinge on the spinal cord. Ligament damage is not likely since bony fracture often occurs prior to ligament rupture (Reference 3).

5.2.1.2 Static/quasi-static Loading in Vulnerable Individuals

For static/quasi-static loading in a vulnerable person the force tolerance was estimated to be 500 lb. This value was selected since it is approximately one standard deviation from the mean of compression injury values calculated by Maiman, et al. (Reference 3) and two standard deviations from the compression tolerance value used for average individuals under static/quasi-static pure axial loading (Reference 13). While this 500 lb. value is conservative, it provides a minimum expected fracture tolerance for any individual. Injuries expected from exceeding the loading tolerance are compression fractures and burst fractures. The general term "compression fracture" encompasses the specific injury mechanisms of a Jefferson fracture (C2 fracture), a multipart axis fracture (C1 fracture), and a loss of vertebral body height. These fractures range in severity from major to fatal with most fractures occurring in the C4 to C6 vertebrae. There is a high risk of neurological damage or fatality associated with the burst fracture, since bony particles may impinge on the spinal cord. Ligament damage is not likely since bony fracture often occurs prior to ligament rupture (Reference 3).

5.2.1.3 Dynamic/impulse Loading in Average Individuals

When loading occurs at a rate of 15 ft/sec or more, the injury tolerances are different from those for static/quasi-static loading conditions. Sufficient experimental evidence was available to separate the magnitude inputs for dynamic axial compression into three categories. The first limit is the same as the static/quasi-static case, with loads less than 1,080 lb not expected to produce a significant injury (Reference 13). An intermediate magnitude range, 1,080 to 1,350 lb, relates to a significant chance for general compression fractures (Jefferson fracture (C2 fracture), multipart axis fracture (C1 fracture), and loss of vertebral body height). The lower limit was based on Nightingale, et al. (Reference 13), and the upper limit was based on Alem, et al. (Reference 12). The compressive fractures may be fatal; however, the chance for fatality is less in this central range than for loads over 1,350 lb. The 1,350 lb limit for severe fracture is based upon the average peak load experienced by eight cadavers during dynamic experimentation by Alem, et al. (Reference 12). Above this level, severe or fatal injury is likely, with burst fractures occurring more frequently. The burst fracture also increases the risk of neurological damage and fatality. These fracture types are most commonly found in the C4 to C6 vertebrae, with the fracture affecting the vertebral body and possibly the spinal cord.

5.2.1.4 Dynamic/impulse Loading in Vulnerable Individuals

For dynamic/impulse situations where vulnerable individuals are involved, Culver, et al. (Reference 21) determined that the minimum magnitude at which injury is likely is 810 lb. Between 810 and 1,080 lb, the risk for general compression fractures (Jefferson fracture (C2 fracture), multipart axis fracture (C1 fracture), and fractures of the vertebral body) is significant. Above 1,080 lb, the likelihood for compressive fracture is increased, as well as the chance for neurological damage or fatal injury from burst-style fractures (based on Nightingale, et al., Reference 13). Over 810 lb, the injuries may range from major to fatal and are most likely to occur in the C4 to C6 vertebrae. The vertebral body is the most likely part of the cervical spine to be affected. However, particularly at higher magnitudes and with the burst-style fracture, spinal cord damage may also result.

5.2.2 Combined Compression-Flexion of the Cervical Spine

For combined compression and flexion, tolerances have been determined for both the force and moment components of the loading. The interactive effects of the moments and forces on the injury tolerance levels are not well understood. The moment tolerances described are for flexion and are based on the work of Mertz and Patrick (Reference 18) and Alem, et al. (Reference 12). The force tolerances are based on studies of compression with flexion (e.g., Sances, et al., Reference 22) and are different from those for pure compression. Figure 9 demonstrates the branched criterion for the compression-flexion loading direction.

5.2.2.1 Static/quasi-static Loading in Average Individuals

Moments

The magnitude of the input moments are based on the flexion moment injury criteria proposed by Mertz and Patrick (Reference 18) and on experimental work by Alem, et al. (Reference 12). Moments below 65 ft-lb are unlikely to cause significant injury. Moments between 65 and 125 ft-lb are likely to cause ligamentous injury, and moments greater than 125 ft-lb are likely to produce bony fractures and structural damage. The lower tolerance limits are considered reasonably conservative, since they were determined with live volunteers. Ligamentous injury consists of torn or ruptured posterior longitudinal ligaments and is considered a minor injury. At higher loading levels, ligamentous injury may combine with dislocation to produce a major injury. Possible fractures include wedge fractures, teardrop fractures, and burst fractures. While all fractures are at least major injuries, severe injuries involving neurological damage and fatalities are also possible. Fractures are most likely to occur in the lower cervical vertebrae (C4 to C6 for burst fractures, C5 to T1 for wedge fractures). The burst and wedge fractures do not usually affect the surrounding ligaments, but the teardrop fracture can disrupt the ligaments and the intervertebral disk.

Forces

The force tolerance for an average individual under static/quasi-static compression-flexion loading is divided into four categories. For the first range, forces under 325 lb, significant injury is unlikely. At levels above 325 lb, bilateral locked facets may be produced (Reference 14). Bilateral locked facets are dislocations of the interfacetal joints; they require a significant off-axis component in addition to the compressive force. This injury can occur anywhere along the cervical spine (C2 to C7) and may be accompanied by extensive ligament disruption (interspinous ligament, intertransverse

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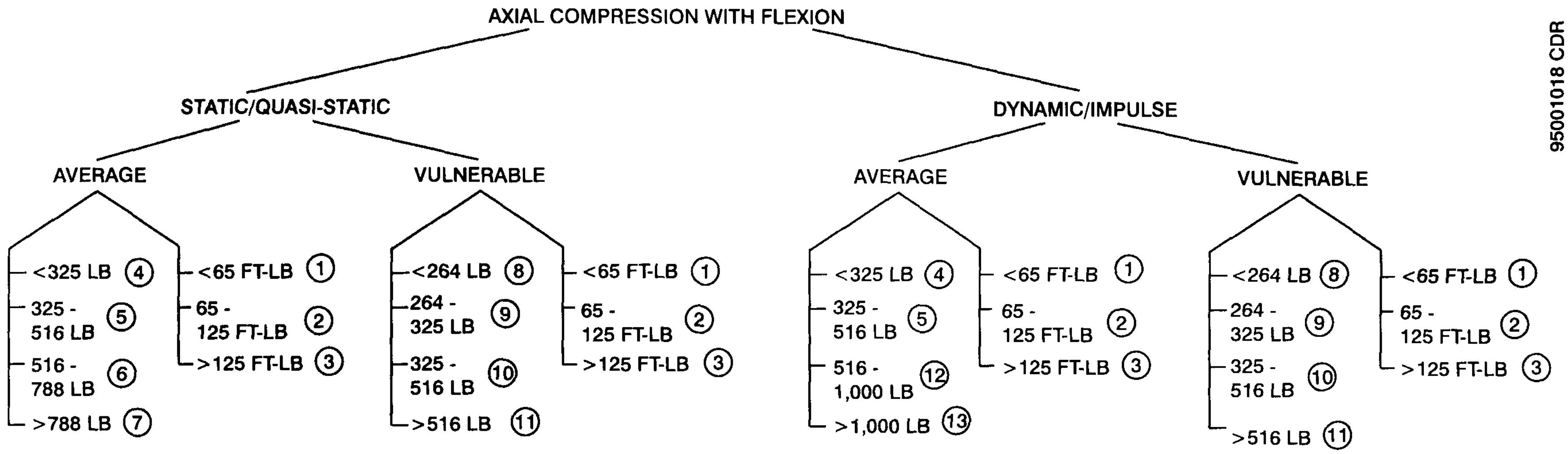

Figure 9.
Injury criterion for compression-flexion loading of the cervical spine.

Table 9.	
Legend for Figure 9. Injury criterion for compression-flexion loading of the cervical spine.	
1.	Injury expected: None Based on Mertz and Patrick (Reference 18).
2.	Injury expected: Ligamentous injury Injury location: Posterior longitudinal ligaments Injury severity: Minor Based on Mertz and Patrick (Reference 18) and Alem, et al. (Reference 12).
3.	Injury expected: Bony fracture (wedge, teardrop, and burst fractures) Injury location: C4 to T1 Injury severity: Major to Fatal Based on Alem, et al. (Reference 12).
4.	Injury expected: None Based on Bauze and Ardran (Reference 14).
5.	Injury expected: Bilateral facet dislocation, when combined with significant off-axis loading Injury location: Dislocation of interfacetal joints Injury severity: Major Based on Bauze and Ardran (Reference 14) and Pintar, et al. (Reference 23).
6.	Injury expected: Bony fracture (wedge, burst, teardrop) Injury location: C4 to T1 Injury severity: Major to Fatal Based on Pintar, et al. (Reference 23) and Pintar, et al. (Reference 24).
7.	Injury expected: Severe fracture with high risk of general fracture (burst, wedge, teardrop) Injury location: C4 to T1 Injury severity: Major to Fatal Based on Pintar, et al. (Reference 24).
8.	Injury expected: None Based on minimal value for fracture from Pintar, et al. (Reference 24).
9.	Injury expected: Bony fracture Injury location: C4 to T1 Injury severity: Major to Fatal Based on minimal value for fracture from Pintar, et al. (Reference 24) and Bauze and Ardran (Reference 14).
10.	Injury expected: Bilateral locked facets Injury location: Dislocation of interfacetal joints Injury severity: Major Based on Bauze and Ardran (Reference 14) and Pintar, et al. (Reference 23).
11.	Injury expected: Severe fracture with high risk of general fracture (burst, wedge, teardrop) Injury location: C4 to T1 Injury severity: Major to Fatal Based on Pintar, et al. (Reference 23).
12.	Injury expected: Bony fracture (burst, wedge, teardrop) Injury location: C4 to T1 Injury severity: Major to Fatal Based on Pintar, et al. (Reference 23) and Sances, et al. (Reference 22).
13.	Injury expected: Severe bony fracture with high risk of general fracture (burst, wedge, teardrop) Injury location: C4 to T1 Injury severity: Major to Fatal Based on Sances, et al. (Reference 22).

ligament, capsular ligament, ligamenta flava, and annulus). When the force magnitude reaches 516 lb, there is a significant chance of general fracture (Reference 23). When the axial compressive force reaches 788 lb, the risk of general fracture is high, with an increased chance of burst fractures (Reference 24). The general fractures include wedge, burst, and teardrop fractures, which may range from major to fatal in severity. These injuries are most likely to occur in the lower cervical spine (C4 to C6 for burst fractures, C5 to T1 for wedge fractures) and affect the vertebral body and possibly the spinal cord. The burst and wedge fractures do not usually affect the surrounding ligaments, but the teardrop fracture can disrupt the ligaments and the intervertebral disk.

5.2.2.2 Static/quasi-static Loading in Vulnerable Individuals

Moments

No distinction can be made for moment tolerances between average and vulnerable individuals in compression-flexion. The flexion testing performed was primarily on live volunteer subjects and is considered to be conservative for normal individuals. However, these values should not be considered conservative for vulnerable individuals. The magnitude of the input moments are determined based on the flexion moment injury criteria proposed by Mertz and Patrick (Reference 18) and on experimental work by Alem, et al. (Reference 12). Moments below 65 ft-lb are unlikely to cause significant injury. Moments between 65 and 125 ft-lb are likely to cause ligamentous injury and may cause structural injury, and moments greater than 125 ft-lb are likely to produce bony fractures and structural damage. Ligamentous injury consists of torn or ruptured posterior longitudinal ligaments and will be either a minor injury, or, at higher loading levels, ligament damage may combine with dislocation to produce a major injury. Likely fractures include wedge fractures, teardrop fractures, and burst fractures, with the fractures ranging in severity from major to fatal. While all fractures are major injuries, the burst fracture is often a severe or fatal injury, since neurological damage is a significant possibility. Fractures are most likely to occur in the lower cervical vertebrae (C4 to C6 for burst fractures, C5 to T1 for wedge fractures). The burst and wedge fractures do not usually affect the surrounding ligaments, but the teardrop fracture can disrupt the ligaments and the intervertebral disk.

Forces

There is little experimental evidence to provide tolerance levels for vulnerable individuals in compression-flexion. However, the minimum value for wedge fractures reported by Pintar, et al. (Reference 24) was 264 lb. This value can be considered a very conservative minimum value at which fracture may occur. Bi-lateral locked facets are expected at forces over 325 lb (Reference 14) and general fractures are expected at forces over 516 lb (Reference 23). Bilateral locked facets are dislocations of the interfacetal joints; they require a significant off-axis component in order to occur. This injury can occur anywhere along the cervical spine (C2 to C7) and may be accompanied by extensive ligament disruption (interspinous ligament, intertransverse ligament, capsular ligament, ligamenta flava and annulus). The general fractures will include burst, wedge, and teardrop fractures, which may range from major to fatal in severity. The burst fractures occur more often at higher magnitudes and increase the risk of neurological damage and fatality. These injuries are most likely to occur in the lower cervical spine (C4 to C6 for burst fractures, C5 to T1 for wedge fractures).

5.2.2.3 Dynamic/impulse Loading in Average Individuals

Moments

No distinction can be made for compression-flexion moment tolerances between static and dynamic loading rates. The flexion testing performed was primarily quasi-static; however, no experimental information was located on the dynamic effects of flexion. The magnitude of the input moments are determined based on the flexion moment injury criteria proposed by Mertz and Patrick (Reference 18) and on experimental work by Alem, et al. (Reference 12). Moments below 65 ft-lb are unlikely to cause significant injury. Moments between 65 and 125 ft-lb are likely to cause ligamentous injury, and moments greater than 125 ft-lb are likely to produce bony fractures and structural damage. Ligamentous injury consists of torn or ruptured posterior longitudinal ligaments, and will be either a minor injury or, at higher loading levels, may combine with dislocation to produce a major injury. Possible fractures include wedge fractures, teardrop fractures, and burst fractures, and range from major to fatal in severity. While all fractures are major injuries, the burst fracture has a significant chance of producing neurological damage, a severe injury, or a fatal injury. The fractures are most likely to occur in the lower cervical vertebrae (C4 to C6 for burst fractures, C5 to T1 for wedge fractures). The burst and wedge fractures do not usually affect the surrounding ligaments, but the teardrop fracture can disrupt the ligaments and the intervertebral disk.

Forces

Under dynamic/impulse conditions, the force tolerances are similar to those for the static/quasi-static condition, except that a higher maximum limit is imposed, over which severe fractures are likely. The lower force tolerances for dynamic/impulse situations are the same as for the static/quasi-static situation: 325 lb as suggested from the work of Bauze and Ardran, (Reference 14). Below this level, no significant injury is expected. Above this level, bilateral locked facets may result. This injury can occur anywhere along the cervical spine (C2 to C7) and may be accompanied by extensive ligament disruption (interspinous ligament, intertransverse ligament, capsular ligament, ligamenta flava, and annulus). At values over 516 lb, bony fracture is a significant possibility (Reference 23). This will be a conservative value for the dynamic situation. For the dynamic/impulse situation, an additional upper tolerance of 1,000 lb was added, over which severe fractures are likely, with an increased chance of burst fracture and fatality (Reference 22). General fractures include wedge, burst, and teardrop fractures, which may range from major to fatal in severity. These fractures are most likely to occur in the lower cervical spine (C4 to C6 for burst fractures, C5 to T1 for wedge fractures). The burst and wedge fractures do not usually affect the surrounding ligaments, but the teardrop fracture can disrupt the ligaments and the intervertebral disk.

5.2.2.4 Dynamic/impulse Loading in Vulnerable Individuals

Moments

No distinction can be made for compression-flexion moment tolerances between static and dynamic loading rates or between vulnerable and average individuals, except that the tolerances are not considered conservative for those who are vulnerable. The flexion testing performed was primarily quasi-static; however, no experimental information was located on the dynamic effects of flexion. The magnitude of the input moments is determined based on the flexion moment injury criteria proposed by Mertz and Patrick (Reference 18) and on experimental work by Alem, et al. (Reference 12). Moments below 65 ft-lb are unlikely to cause significant injury. Moments between 65 and 125 ft-lb are likely to cause ligamentous injury or bony fracture, and moments greater than 125 ft-lb are highly likely to produce bony fractures and structural damage. Ligamentous injury consists of torn or ruptured posterior longitudinal ligaments and will be either a minor injury or, at higher loading levels, may combine with dislocation to produce a major injury. Possible fractures include wedge fractures, teardrop fractures, and burst fractures, and these range from major to fatal in severity. While all fractures are major injuries, the burst fracture has a significant chance of producing neurological damage, a severe injury, or a fatal injury. The fractures are most likely to occur in the lower cervical vertebrae (C4 to C6 for burst fractures, C5 to T1 for wedge fractures). The burst and wedge fractures do not usually affect the surrounding ligaments, but the teardrop fracture can disrupt the ligaments and the intervertebral disk.

Forces

There is currently little direct experimental evidence to provide force tolerance levels for vulnerable individuals in compression-flexion. The minimum value for wedge fractures reported by Pintar, et al. (Reference 24) was 264 lb. This value is a very conservative minimum tolerance at which fracture may occur. The remainder of the static/quasi-static tolerances for vulnerable individuals match those for average individuals with bi-lateral locked facets expected at values over 325 lb (Reference 14) and general fractures over 516 lb Bilateral locked facets are dislocations of the interfacetal joints, but they require a significant off-axis component in order to occur. This injury can occur anywhere along the cervical spine (C2 to C7) and may be accompanied by extensive ligament disruption (interspinous ligament, intertransverse ligament, capsular ligament, ligamenta flava, and annulus). The 516 lb fracture limit determined by Pintar, et al. (Reference 23) provides the upper limit of magnitude, over which fractures are considered likely to occur. The general fractures will include burst, wedge, and teardrop fractures, which may range from major to fatal in severity. The burst fractures occur at higher magnitudes and increase the risk of neurological damage and fatality. These injuries are most likely to occur in the lower cervical spine (C4 to C6 for burst fractures, C5 to T1 for wedge fractures) and affect the vertebral body and the intervertebral disk.

5.2.3 Combined Compression-Extension of the Cervical Spine

When axial compression and extension are both encountered, a combined loading situation occurs at the neck. Both force tolerances and moment tolerances were determined. The interactive effects of moment and force on the injury tolerances are not well understood. Little experimental evidence is available for use in determining the tolerances in the combined compression-extension direction. For each situation, the moment tolerances were based on the recommended criteria in Mertz and Patrick (Reference 18) and the experimental work of Alem, et al. (Reference 12). No interactions between the force and moment tolerances were incorporated into the criterion. Figure 10 demonstrates the branched criterion for the compression-extension loading direction.

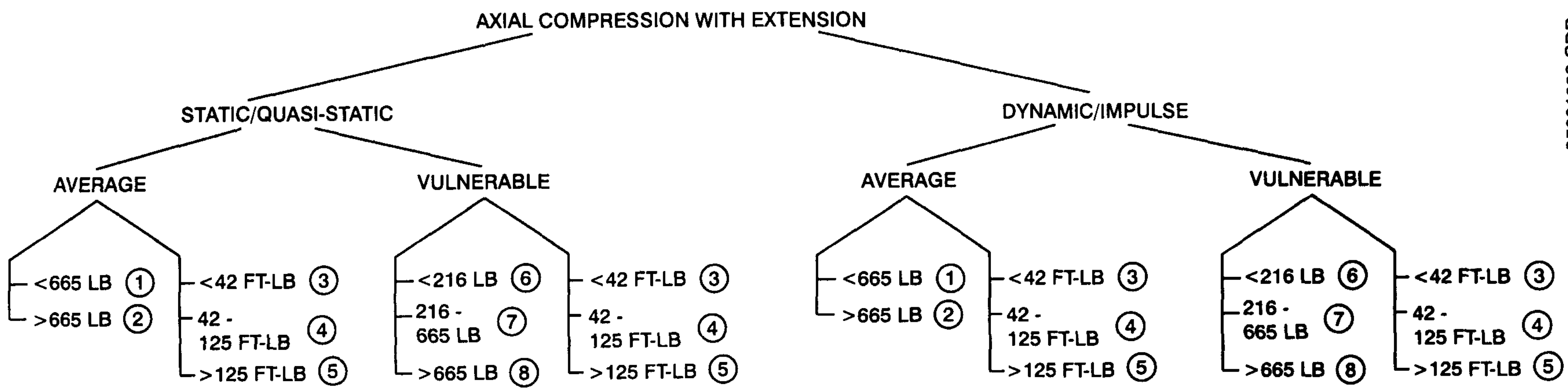

Figure 10.
Injury criterion for combined compress-extension loading of the cervical spine.

Table 10.	
Legend for Figure 10. Injury criterion for combined compression-extension loading of the cervical spine.	
1.	Injury expected: None Based on McElhaney, et al. (Reference 20).
2.	Injury expected: Bony fracture (Jefferson, posterior element, fracture dislocation) Injury location: Upper cervical spine Injury severity: Major to Fatal Based on McElhaney, et al. (Reference 20).
3.	Injury expected: None Based on Mertz and Patrick (Reference 18).
4.	Injury expected: Ligamentous injury Injury location: Anterior longitudinal ligament Injury severity: Minor Based on Mertz and Patrick (Reference 18) and Alem, et al. (Reference 12).
5.	Injury expected: Bony fracture (C1, C2, teardrop, burst) Injury location: Upper cervical spine Injury severity: Major to Fatal Based on Alem et al. (Reference 12).
6.	Injury expected: None Based on minimum value to fracture in McElhaney, et al. (Reference 20).
7.	Injury expected: Bony fracture (Jefferson, posterior element, fracture dislocation) Injury location: Upper cervical spine Injury severity: Major to Fatal Based on McElhaney, et al. (Reference 20).
8.	Injury expected: Severe bony fracture, high risk of bony fracture (Jefferson, posterior element, fracture dislocation) Injury location: Upper cervical spine Injury severity: Major to Fatal Based on McElhaney, et al. (Reference 20).

5.2.3.1 Static/quasi-static Loading in Average Individuals

Moments

The magnitude of the input moments are determined based on the work of Mertz and Patrick (Reference 18) and Alem, et al. (Reference 12). Moments below 42 ft-lb are not likely to cause significant injury. Moments between 42 and 125 ft-lb are likely to cause ligamentous injury, and moments greater than 125 ft-lb are likely to produce bony fractures and structural damage. The anterior longitudinal ligament may rupture or tear, which is a minor injury or, at higher loading levels, the ligament damage may be combined with dislocation and spinal cord injury, which is a major to fatal injury. Possible fracture types include fractures of the C1 and C2, teardrop fractures, and burst fractures. Each of these fractures is particularly dangerous and may cause neurological damage, as well as fatality. The upper cervical spine is the most likely area for injury.

Forces

Fewer studies are available for compression-extension than for compression-flexion situations. The primary injury mechanisms include posterior element fractures and fracture dislocations. If smaller levels of off-axis loading are present, Jefferson, burst, and teardrop fractures may occur. Each of these injuries is at least a major injury, with severe and fatal injuries a distinct possibility. In a study of isolated cervical spines, McElhaney, et al. (Reference 20) tested five specimens quasi-statically in compression-extension postures. Of these, four suffered Jefferson fractures, with the average load to fracture of 665 lb (range 216 to 942 lb). A force tolerance of 665 lb is set for bony fractures in compression-extension loading. This value is similar to the 516-lb limit generally set for compression-flexion bony failure. Below 665 lb, an average person is not expected to experience bony fracture. Above 665 lb, a significant chance of bony fracture exists, although the specific type of bony fracture cannot be predicted. The bony fractures will mostly occur in the upper cervical spine.

5.2.3.2 Static/quasi-static Loading in Vulnerable Individuals

Moments

No distinction can be made for moment tolerances between average and vulnerable individuals under compression-extension loading. The extension testing was performed primarily on live volunteer subjects and, therefore, provides a conservative injury tolerance value. While the stated values are conservative for average individuals, they should be considered values at which significant injury is likely for vulnerable individuals. The moment tolerances are based on the extension moment injury criteria proposed by Mertz and Patrick (Reference 18) and on experimental work by Alem, et al. (Reference 12). Moments below 42 ft-lb are unlikely to cause significant injury. Moments between 42 and 125 ft-lb are likely to cause ligamentous injury, and moments greater than 125 ft-lb are likely to produce bony fractures and structural damage. Ligamentous injury will affect the anterior longitudinal ligament and will be either a minor injury or, at higher loading levels, might be combined with dislocation and spinal cord injury to produce a major to fatal injury. Possible fracture types include C1 and C2 fractures, teardrop fractures and burst fractures. The fractures will range from major to fatal, with neurological damage and fatality significant possibilities. The upper cervical spine is the most likely area to be affected.

Forces

Fewer studies are available for compression-extension than for compression-flexion situations. The primary injury mechanisms include posterior element fractures and fracture dislocations. If smaller levels of off-axis loading are present, Jefferson, burst, and teardrop fractures may occur. For vulnerable individuals, two tolerance levels were set. The tolerance of 216 lb is the minimum force at which fracture may occur (Reference 20). A second tolerance of 665 lb is the level at which a high chance of bony fracture exists (Reference 20). Any of the mechanisms listed may occur, with the upper cervical spine the most likely location for injury. The fractures will range from major to fatal in severity.

5.2.3.3 Dynamic/impulse Loading in Average Individuals

Moments

In the dynamic/impulse loading situation, the moment tolerances are not different than those for the static/quasi-static situation. The magnitude of the input moments are determined based on the extension moment injury criteria proposed by Mertz and Patrick (Reference 18) and on experimental work by Alem, et al. (Reference 12). Moments below 42 ft-lb are not likely to cause significant injury. Moments between 42 and 125 ft-lb are likely to cause ligamentous injury, and moments greater than 125 ft-lb are likely to produce bony fractures and structural damage. Ligamentous injury will affect the anterior longitudinal ligament and will be either a minor injury or, at higher loading levels, might be combined with dislocation and spinal cord injury to produce a major to severe injury. Possible fractures include C1 and C2 fractures, teardrop fractures and burst fractures. The fractures will range from major to fatal, with neurological damage and fatality as significant possibilities. The upper cervical spine is the area most likely to be affected.

Forces

Fewer studies are available for compression-extension than for compression-flexion situations. The static/quasi-static values will be used for the dynamic/impulse situation as well. The primary injury mechanisms include posterior element fractures and fracture dislocations. If smaller levels of off-axis loading are present Jefferson, burst, and teardrop fractures may occur. Each of these injuries is at least a major injury, with severe and fatal injuries a distinct possibility. A tolerance of 665 lb is set for bony fracture (Reference 20). This value is similar to the 516-lb limit generally set for compression-flexion bony failure (Reference 23). Below 665 lb, an average person is not expected to experience bony fracture. Above the tolerance level, a significant chance of bony fracture exists. The bony fractures will mostly occur in the upper cervical spine.

5.2.3.4 Dynamic/impulse Loading in Vulnerable Individuals

Moment

The proposed tolerances for dynamic/impulse loading for vulnerable individuals is the same as for average individuals. The extension testing was performed primarily on live volunteer subjects. While the stated values are conservative, they should be considered values at which significant injury is highly likely for vulnerable individuals, particularly those with bone and joint degeneration. The moment tolerances are based on the extension moment injury criteria proposed by Mertz and Patrick (Reference 18) and on experimental work by Alem, et al. (Reference 12). Moments below 42 ft-lb are unlikely to cause significant injury. Moments between 42 and 125 ft-lb are likely to cause ligamentous injury, and moments greater than 125 ft-lb are likely to produce bony fractures and structural damage. Ligamentous injury will affect the anterior longitudinal ligament and will be either a minor injury or, at higher loading levels, might be combined with dislocation and spinal cord injury to produce a major to fatal injury. Possible fracture types include C1 and C2 fractures, teardrop fractures, and burst fractures. The fractures, will range from major to fatal, with neurological damage and fatality as significant possibilities. The upper cervical spine is the area most likely to be affected.

<u>Forces</u>
Fewer studies are available for compression-extension than for compression-flexion situations. The tolerance values determined for the static/quasi-static situation will be used for the dynamic/impulse situation as well. The primary injury mechanisms include posterior element fractures and fracture dislocations. If smaller levels of off-axis loading are present, Jefferson, burst, and teardrop fractures may occur. For vulnerable individuals, two tolerance levels were set. The tolerance at which fracture can be expected is 216 lb (Reference 20). A second tolerance of 665 lb is the level at which a high chance of bony fracture exists (Reference 20). The fractures will likely occur in the upper cervical spine and will range from major to fatal in severity.

5.2.4 Combined Compression Unspecified Eccentric Loading of the Cervical Spine

When an eccentric load is applied in combination with a compressive load, the injury tolerance will be less than for a purely compressive load. While this is evident from the experimental literature, the direction and magnitude of the off-axis loading were not always reported or measured. Furthermore, in whole cadaver testing, the degree of off-axis loading may be difficult to discern. For these reasons, the category of compressive loading with an unspecified off-axis component has been added. Only tolerances for the compressive force component will be detailed. If the additional component is determined, its tolerance levels can be determined by re-applying the injury criterion with the off-axis component as the primary loading direction. Figure 11 demonstrates the injury criterion for the compression with unspecified eccentric loading.

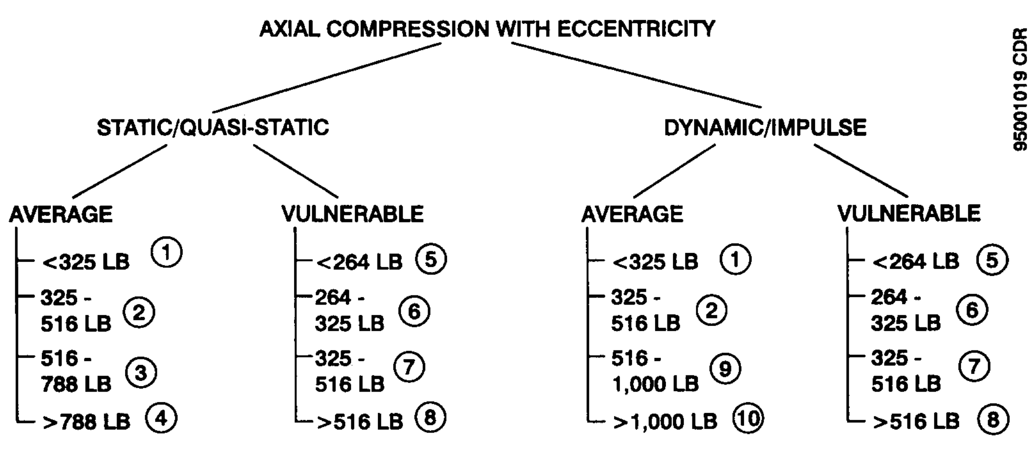

Figure 11.
Injury criterion for axial compression with unspecified eccentric loading of the cervical spine.

Table 11.	
Legend for Figure 11. Injury criterion for axial compression with unspecified eccentric loading of the cervical spine.	
1.	Injury expected: None Based on Bauze and Ardran (Reference 14).
2.	Injury expected: Bilateral locked facets Injury location: Dislocation of the interfacetal joints Injury severity: Minor Based on Bauze and Ardran (Reference 14) and Pintar, et al. (Reference 23).
3.	Injury expected: Bony fracture (wedge, teardrop, burst) Injury location: Lower cervical spine Injury severity: Major to Fatal Based on Pintar, et al. (Reference 23) and Pintar, et al. (Reference 24).
4.	Injury expected: Severe bony fracture (wedge, teardrop, burst) Injury location: Lower cervical spine Injury severity: Major to Fatal Based on Pintar, et al. (Reference 24).
5.	Injury expected: None Based on minimum fracture value for Pintar, et al. (Reference 24).
6.	Injury expected: Bony fracture (wedge, teardrop, burst) Injury location: Lower cervical spine Injury severity: Major to Fatal Based on Pintar, et al. (Reference 24) and Bauze and Ardran (Reference 14).
7.	Injury expected: Bilateral locked facets, bony fracture (wedge, teardrop, burst) Injury location: Dislocation of the interfacetal joints, lower cervical spine Injury severity: Major to Fatal Based on Bauze and Ardran (Reference 14) and Pintar, et al. (Reference 23).
8.	Injury expected: Severe bony fracture (wedge, teardrop, burst) Injury location: Lower cervical spine Injury severity: Major to Fatal Based on Pintar, et al. (Reference 23).
9.	Injury expected: Bony fracture (wedge, teardrop, burst) Injury location: Lower cervical spine Injury severity: Major to Fatal Based on Pintar, et al. (Reference 23) and Sances, et al. (Reference 22).
10.	Injury expected: Severe fracture, high risk of general fracture (wedge, teardrop, burst) Injury location: Lower cervical spine Injury severity: Major to Fatal Based on Sances, et al. (Reference 22).

5.2.4.1 Static/quasi-static Loading in Average Individuals

The minimum value at which injury is expected is 325 lb (Reference 14). Over this tolerance, bilateral locked facets may occur. Bilateral locked facets involve the dislocation of the interfacetal joints and generally require a significant off-axis loading component. This injury can occur anywhere along the cervical spine (C2 to C7) and may be accompanied by extensive ligament disruption (interspinous ligament, intertransverse ligament, capsular ligament, ligamenta flava, and annulus). Above 516 lb, general compressive type fractures can be expected (Reference 23). These fractures include wedge fractures, teardrop fractures, and burst fractures. While wedge and burst fractures mostly affect the vertebral body, teardrop fractures also produce damage to the ligaments. The burst fracture also may produce spinal cord injury as bony particles impinge on the spinal cord. At force magnitudes over 788 lb, the risk of fracture is high, as is the risk of spinal cord injury or fatality (Reference 24). These injuries are most likely to occur in the lower cervical spine (C4 to C6 for burst fractures, C5 to T1 for wedge fractures) and affect the vertebral body and the intervertebral disk.

5.2.4.2 Static/quasi-static Loading in Vulnerable Individuals

There is currently little direct experimental evidence to provide tolerance levels for vulnerable individuals in compression with eccentricity. However, a wedge fracture reported by Pintar, et al. (Reference 24) occurred at 264 lb. This value can be considered a minimum value at which a fracture may occur. The minimum value at which bilateral locked facets are expected is 325 lb. (Reference 14). Bilateral locked facets involve the dislocation of the interfacetal joints and generally require a significant off-axis loading component. This injury can occur anywhere along the cervical spine (C2 to C7) and may be accompanied by extensive ligament disruption (interspinous ligament, intertransverse ligament, capsular ligament, ligamenta flava, and annulus). General fractures are likely to occur at forces over 516 lb. (Reference 23). The general fractures will include wedge, burst, and teardrop fractures, which may range from major to fatal in severity. The burst fractures increase the risk of neurological damage and fatality. These injuries are most likely to occur in the lower cervical spine (C4 to C6 for burst fractures, C5 to T1 for wedge fractures) and affect the vertebral body and the intervertebral disk.

5.2.4.3 Dynamic/impulse Loading in Average Individuals

The lower magnitude limit for injury during dynamic/impulse situations is the same as for the static/quasi-static situation and for the compression-flexion case; 325 lb, as suggested from the work of Bauze and Ardran (Reference 14). Below this level, no significant injury is expected. Above this level, bilateral locked facets may result. This injury can occur anywhere along the cervical spine (C2 to C7) and may be accompanied by extensive ligament disruption (interspinous ligament, intertransverse ligament, capsular ligament, ligamenta flava, and annulus). A tolerance of 516 lb is also chosen for the minimum limit for bony fracture (Reference 23). This will be a conservative value for the dynamic situation, but it provides a reasonable minimum limit for fracture. A maximum tolerance of 1,000 lb is set as a limit over which fracture is highly likely and severe fractures are expected (Reference 22). The general fractures will include wedge, burst and teardrop fractures, which may range from major to fatal in severity. The burst fractures also include the risk of neurological damage and an increased risk of fatality. These injuries are most likely to occur in the lower cervical spine (C4 to C6 for burst fractures, C5 to T1 for wedge fractures) and affect the vertebral body and the intervertebral disk.

5.2.4.4 Dynamic/Impulse Loading in Vulnerable Individuals

There is currently little direct experimental evidence to provide tolerance levels for vulnerable individuals in compression with eccentricity. The values for static/quasi-static loading for vulnerable individuals are used. The minimum value for a wedge fracture reported by Pintar, et al. (Reference 24) was at 264 lb. This value can be considered a minimum value at which fracture may occur. The minimum value at which bilateral locked facets are expected is 325 lb (Reference 14). Bilateral locked facets involve the dislocation of the interfacetal joints and generally require a significant off-axis loading component. This injury can occur anywhere along the cervical spine (C2 to C7) and may be accompanied by extensive ligament disruption (interspinous ligament, intertransverse ligament, capsular ligament, ligamenta flava, and annulus). General fractures are likely to occur at forces over 516 lb (Reference 23). The general fractures will include wedge, burst, and teardrop fractures, which may range from major to fatal in severity. The burst fractures increase the risk of neurological damage and fatality. These injuries are likely to occur in the lower cervical spine (C4 to C6 for burst fractures, C5 to T1 for wedge fractures) and affect the vertebral body and the intervertebral disk.

5.3 COMPARISON TO OTHER INJURY CRITERIA

The injury criterion structure and, specifically, this neck injury criterion were designed to provide the maximum amount of information to the user. This was accomplished by setting up the criterion in a branched structure with inputs such as loading rate/duration and subject condition. The branched structure is a "living structure", with each branch updateable as more experimental and tolerance information becomes available.

The injury criterion structure developed in the program is an improvement over previous injury tolerance guidelines. Injury criteria that are developed based on the structure are updateable and provide more detailed information to the user. The current criterion structure also retains the experimental references and textual descriptions of the possible injury types, locations, and severities. These references and descriptions provide the user with more injury information than is available with a single-level criterion.

Overall, the injury tolerances incorporated in the neck injury criterion compare well to those previously published. The 1,080-lb level selected as the minimal tolerance for fracture in pure axial compression is the same as that suggested by Raddin, et al. (Reference 6) and experimentally determined by Nightingale, et al. (Reference 13). It is also the same as one of the possible criteria suggested by McElhaney and Myers (Reference 8). The tolerance for severe fracture in the dynamic/impulse loading situation (1,350 lb) relates to one standard deviation of the 1,080-lb value and to the mean of the peak load to failure as determined by Maiman, et al. (Reference 3). This value was also proposed by McElhaney and Myers (Reference 8) as a possible injury criteria for axial compression. No proposed tolerances were found specifically for vulnerable individuals.

For the combined loading scenarios of compression-flexion and compression-extension, the tolerances selected in this report correspond to those suggested by Mertz and Patrick (Reference 18) and by Alem, et al. (Reference 12). The Mertz and Patrick criteria have been generally accepted in the automotive environment. The values proposed for the force tolerance of the combined loading scenario are similar to those suggested by McElhaney and Myers (Reference 8) and Raddin, et al. (Reference 6). Raddin, et al. proposed a slightly higher axial compression force (600 lb) and a different bending moment (70 ft-lb) than the static/quasi-static values selected for average individuals (516 lb; and 65 ft-lb and 42 ft-lb for ligamentous injury in flexion and extension, respectively). With the large variations between individuals, these differences are not necessarily significantly different.

6.0 TASK 4 - DEVELOP INJURY ASSESSMENT SYSTEM STRUCTURE

An Injury Assessment System (IAS) was developed to demonstrate an approach to predicting injuries using manikins and the injury criterion structure developed in this program. The injury criterion structure was designed to require loading information as input data, producing injury information as the output. Within the IAS, the input loading information required by the injury criterion would be obtained from an instrumented manikin after that manikin-based data is converted into human-based data. Injury information would be the output from the criterion structure, which, within the system, would be a software-based program. The manikin-to-human correlations and the injury criterion will be in a software format to automate the process for the user. Incorporating software into the system also allows for future enhancements or upgrades to the system. For example, a graphical display of the body segments can highlight specific locations where possible injuries are predicted to occur.

The IAS is comprised of three components: (1) human injury criteria software, (2) an instrumented manikin, and (3) correlation software (Figure 12). The first component, human injury criteria software, relates human-based loads and accelerations to the injuries sustained by the human as a result of the loading. The injury criterion structure developed in this Phase I program serves as the basis of this IAS component. The second component is an instrumented manikin (modified as necessary) that will measure the appropriate loading information for use in the criteria software. The third component, correlation software, will serve as the transition between the manikin-based measurements and the human-based injury criteria inputs.

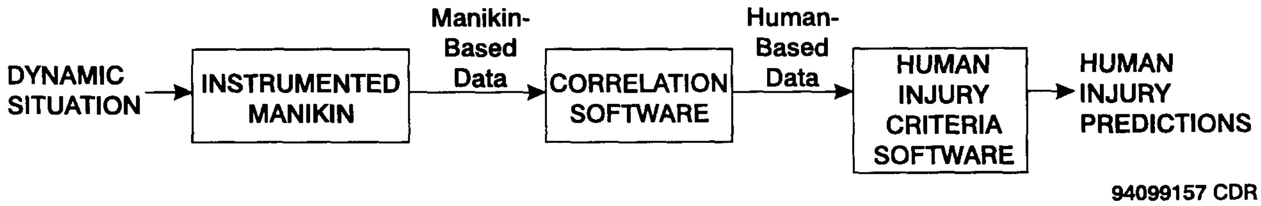

Figure 12.
Injury assessment system (IAS).

This three-part IAS measures the loads and accelerations experienced by a manikin in a dynamic environment and relates them to the injuries which a human would experience in the same situation. The development of the IAS relies heavily on experimental and medical data, novel correlations between the manikin measurements and the human-based data, and upon the current status of manikin technology. Since the IAS is formulated in three components, the system can be upgraded with advancements in any of these areas.

7.0 SUMMARY

The following key points summarize the work conducted in this Phase I program.

- In military mishap situations, the most likely body segments to be injured include the head, the thorax, and the upper and lower extremities.
- In Air Force ejections, the spine and the neck are also particularly vulnerable to injury.
- The number of severe neck injuries in Air Force ejections is not significant. However, the total number of neck injuries, including soft-tissue damage such as sprains and strains, is significant.
- In Air Force Class A mishaps involving ejections with ACES II ejection seats, the incidence of cervical fracture was reduced over the ejections with all types of ejection seats.
- The thoracic spine is particularly vulnerable during Air Force ejections. However, the rate of thoracic spine injuries was significantly reduced with the use of ACES II ejection seats.
- Experimental data from the literature were reviewed to determine typical neck loading mechanisms and load magnitudes causing injuries.
- Eleven, neck loading directions were identified. These loading directions include axial compression, axial tension, flexion, extension, horizontal shear, rotation, lateral bending, compression-extension, compression-flexion, tension-extension, and tension-flexion.
- Compression-flexion loading is the most common loading mechanism in spinal cord injury in the general population.
- The human injury criterion structure requires inputs of loading direction, off-axis loading direction, subject condition, load rate/duration and load magnitude to produce outputs of injury mechanism, injury location, injury severity, and the references used to develop the tolerances.
- The branched injury criterion structure offers a more detailed assessment of injuries than has been previously made available.
- The injury criterion structure can be updated and revised as new experimental information becomes available.
- The injury criterion structure was developed to keep the tolerances closely linked to the references used to develop them. Identifying references in the criterion allows for revision as new experimental data becomes available and allows the user to check the reference if necessary.
- The data from different experiments were difficult to compare due to variations in testing procedures. In the development of the neck injury criterion , these differences were taken into account by several methods, including focusing on the whole spine and cadaver work, dividing the neck injury criterion into different branches for subject condition and loading rate/duration, and incorporating a direction-loading branch with an unspecified off-axis loading component.
- The neck injury criterion was developed to predict neck injuries that typically occur under pure axial compression, compression-flexion, compression-extension and

compression with eccentricity loads. A branched criterion structure was developed for each one of these neck loading directions.

- In addition to the loading directions, other neck injury criterion inputs include load rate/duration (static/quasi-static or dynamic/impulse), subject condition (average or vulnerable), and load magnitude.
- The tolerances presented as part of the neck injury criterion are very conservative. Even tolerances for average subjects are conservative, since they are generally based on cadaver or volunteer testing.
- The injury assessment system is a three-part system that integrates the use of manikins, correlates manikin loading data to human-based data, and predicts injury with an injury criterion.
- The software format of the injury assessment system provides the user with a simple-to-use tool to assess injury directly from manikin testing.

8.0 CONCLUSIONS

The following conclusions have been made from the Phase I program:

- Air Force Safety Agency records and databases were a helpful tool in developing a conceptual understanding of the injuries that occur in military mishaps; however, the lack of quantitative information prohibited the incorporation of this information directly into the neck injury criterion.
- Air Force Safety Agency individual mishap records revealed a variety of unique injury-causing mishaps illustrating the need to improve safety technology using a comprehensive injury criterion.
- The amount of information available in the experimental literature limited the level of detail in the neck injury criterion and resulted in varying levels of detail for different branches in the criterion.
- Experimental studies were difficult to compare because test procedures varied among the studies.
- Including subject conditions and a measure of the load rate and duration into the criterion provided a valuable means of incorporating a variety of experimental studies into the same criterion.
- Collecting mishap scenarios, injury mechanisms, and experimental studies into a database format made data comparison and evaluation easier.
- Establishing a database of injury mechanisms helped to distinguish between pure and combined loading situations of the neck, and their corresponding differences in injury tolerance.
- Using a branched structure was an effective means of forming an injury criterion that could be easily updated in the future.
- Using a branched criterion structure was an effective means of incorporating detailed information into the criterion.
- Manikin output data can be correlated with human injury predictions through the use of a comprehensive injury assessment system.

9.0 RECOMMENDATIONS

The assessment of possible injury to humans is potentially a powerful design and research tool. Recommendations are made in this section to continue developing the injury assessment system and future similar systems that utilize computer modeling and analysis techniques.

1. **Conduct additional mishap reviews.** Review individual mishap records from Naval and Army Safety Agency records, as well as Air Force Safety Agency records from all classes of mishaps, to provide a complete conceptual overview of the injuries from all military-related scenarios.
2. **Perform accident reconstructions.** Perform aircraft accident reconstructions to quantify the relationship between load and injury in military mishap scenarios. While this information is not available in the general mishap files, and may not be obtainable for all mishaps, reconstructing common injury scenarios would provide a valuable insight into the prediction of injury from the military mishap environment.
3. **Expand experimental testing.** The neck injury criterion could be improved by expanding experimental testing on the cervical spine to include special populations and dynamic and impulse loading rates and durations.
4. **Investigate injury parameters**. Investigate other types of input parameters that may assist in injury prediction. Options include strain, displacement, and impulse measurements.
5. **Use computer/analytical modeling.** Use computer and analytical models to incorporate experimental information from individual vertebrae and functional spinal units into the injury criteria. Incorporating the injury criteria into the computer modeling realm would eventually reduce the need for cadaver and volunteer testing. Through the use of more complex occupant simulations, computer modeling may also reduce the need for expensive manikin and field testing.
6. **Provide a measure of injury probability.** Develop a means to measure injury probability. This parameter is lacking in current injury assessment systems, despite extensive collections of recorded automobile and aircraft mishaps in which an injury was produced. Artificial intelligence methods such as neural networks are available and provide a means by which the collected information may be used to assess probability. These methods would provide the means to learn from past experience and, with the use of existing information, would lead to a more comprehensive understanding of the injury.
7. **Evaluate and re-design manikin hardware.** Redesign the manikin to improve its injury assessment capability. An improved manikin could be integrated with the injury assessment system.

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APPENDIX A
AIR FORCE MISHAP DATABASES AND NARRATIVES

The following database (Appendix A-1) contains summaries of the 64 Air Force Safety Agency mishap files reviewed. Some of the data contained in this database was sorted from an Air Force Safety Agency database which contained information on Class A and B mishaps from 1971 to the present (1994). The Safety Agency database contains more information than is reported here. Data specific to this program was collected from the mishap files and is contained, to a large extent, in the following database and in the narrative summaries in Appendix A-2.

Key to abbreviations:

AC (or A/C)	=	aircraft
AGL	=	above ground level
KEAS	=	knots equivalent air speed
KIAS	=	knots in air speed
EF	=	ejection force
ESO (MESO)	=	electronics systems officer
fx	=	fracture
GLOC	=	gravity-induced loss of consciousness
IP	=	instructor pilot
IWG	=	impact with ground
L	=	left
MB seats	=	Martin-Baker seats
MC	=	mishap crew
MP	=	mishap pilot
NAV	=	navigator
NVG	=	night vision goggles
OCS	=	opening chute shock
P	=	pilot
PLF	=	parachute landing fall
R	=	right
WSO (MWSO)	=	weapons systems officer
yo	=	years old

Injury Categorizations

Categorizations relate to the severity of injury to the crewmember.
NONE - no injury occurred
MINOR - a minor injury that does not require time off from duty
MAJOR - a serious injury, requiring hospitalization or time missed from duty
FATAL - the injured crew member did not survive

APPENDIX A-1
DATABASE OF 64 FILES REVIEWED FROM AIR FORCE SAFETY AGENCY MISHAP RECORDS

Appendix A-1

Individual mishap records database

Number	Person	Injury	Position	Aircraft	Altitude	Speed	Attitude	Injury cause #1	Injury location
1	1	MAJOR	PILOT	HH60G			no ejection capability	IW water, thrown from AC	multiple
1	3	FATAL	CREW	HH60G			no ejection capability	IW water,co-pilot struck by rotor blade	multiple
1	9	FATAL	PASSENGERS	HH60G			no ejection capability	IW water	multiple
2	1	MAJOR	PILOT	F16	50	175	20 right bank, 5 nose up	EF, PLF, ?	spine
3	1	FATAL	PILOT	U2R	450	125	30 bank, 80 nose D, 50 deg/sec roll	IWG, chute didn't open	multiple
4	1	NONE	PILOT	F16	900	190	30 left bank	none	none
5	1	FATAL	PILOT	F16	0		70 nose down, 160 right bank	struck in head, entangled while ejecting	multiple
6	5	FATAL	CREW	C130B			no ejection capability	IWG, FIRE	
6	9	INJURED	CIVILIANS	C130B			on ground		
6	11	FATAL	CIVILIANS	C130B			on ground		
7	1	MAJOR	PILOT	F4	9,000.00	320	90 left bank, 20 nose down	EF, poor positioning	spine
7	2	MAJOR	WSO	F4	9,000.00	320	90 left bank, 20 nose down	FLAIL	extremity
8	1	FATAL	PILOT	F15			no attempt to eject	IWG, controlled flight into mountain	head
9	1	MAJOR	PILOT	F111				PLF, did not brace for impact	spine
9	2	MINOR	WSO	F111				impacted canopy	head
10	1	MAJOR	PILOT	F4	2,000.00		50 nose down, 60 bank	struck by helmet	head
10	2	MINOR	CREW	F4	2,000.00		50 nose down, 60 bank	EF	neck
11	1	FATAL	PILOT	F15			no eject attempt, flight into ground	IWG	multiple
11	2	FATAL	WSO	F15			no eject attempt, flight into ground	IWG	multiple
12	1	FATAL	PILOT	UH-1N			no ejection capability	IW cockpit, whiplash at belt	multiple
12	2	FATAL	ENGINEER	UH-1N			no ejection capability	IW AC interior, hit hard enough to break helmet	multiple
12	3	MAJOR	CO-PILOT	UH-1N			no ejection capability	thrown clear during AC roll	head, extremity
12	4	MAJOR	MECHANIC	UH-1N			no ejection capability	tumbled, thrown clear	extremity, thorax
13	1	FATAL	PILOT	F4	500	250	45 right bank, 50 nose down	IWG, incomplete eject sequence	multiple
13	2	MINOR	WSO	F4	800	250	45 right bank, 50 nose down	FLAIL	extremity
14	1	FATAL	PILOT	F15			no eject attempt, crash into water	IW water (in AC)	multiple
15	8	FATAL	CREW	C141B			no ejection capability	loss of occupiable space, fire	multiple
16	1	MINOR	PILOT	F4	3,000.00			contact with cockpit	extremity
16	2	MINOR	WSO	F4	3,000.00			EF	spine
17	6	FATAL	CREW	HH3E			no ejection capability	IWG	multiple
18	6	FATAL	PILOT, CIV	A-10A			no attempt to eject	IWG	multiple
18	84	INJURED	CIVILIANS	A-10A					
19	1	FATAL	PILOT	A7D			no eject attempt, flight into ground	IW cockpit	multiple
20	6	FATAL	CREW	C130E			crash landing just short of runway	IWG (in AC), FIRE	multiple
21	1	MINOR	PILOT	F4	500	225	5 nose down	EF	neck
21	2	MAJOR	WSO	F4	500	225	5 nose down	EF	spine
22	1	MAJOR	PILOT	A-10A	140	130	12 nose down, 15 right bank	PLF, (older age), EF,?	spine

Individual mishap records database

Number	Person	Injury	Position	Aircraft	Altitude	Speed	Attitude	Injury cause #1	Injury location
23	1	MAJOR	PILOT	F111	2,400.00	180	33 right bank, 8 nose up	PLF - hard landing in capsule	spine
23	2	MAJOR	WSO	F111	2,400.00	180	33 right bank, 8 nose up	PLF - hard landing, overweight guy	spine
24	1	MAJOR	PILOT	A-10A	400	160	45 nose down, 90 right bank	PLF, EF, ?	spine
25	1	MAJOR	PILOT	A7D	1,000.00	230	right wing down, 17.5 angle of attack	OCS, EF	neck
26	1	MAJOR	PILOT	F4	3,000.00	225	out of control	EF, out of position	spine
26	2	MINOR	WSO	F4	3,000.00	225	out of control	chute deployment	multiple
27	1	MAJOR	PILOT	F4	1,100.00	210	level	EF, unaware	spine
27	2	MAJOR	WSO	F4	1,100.00	210	level	EF	spine
28	1	MAJOR	PILOT	F15	5,100.00	200	50 nose down	seat tumbled, hit by debris	head
29	1	FATAL	PILOT	F4				IWG,ejection incomplete	multiple
29	2	MAJOR	WSO	F4	300	300		EF, or PLF	spine
30	1	MINOR	PILOT	MH60G			no ejection capability	ditching	extremity
30	2	NONE	CO-PILOT	MH60G			jumped from AC prior to ditching	none	none
30	3	MINOR	Flt Engine	MH60G			sitting on floor during ditching	impact with water (in AC)	back, extremity
30	4	FATAL	RESCUEMAN	MH60G			missing, jumped prior to ditching	missing	
30	5	MAJOR	RESCUEMAN	MH60G			fell 60ft., poorly timed water jump	impact with water (jumped from AC)	abdomen
31	1	MINOR	PILOT	B52			low level ejection upwards		extremity
31	2	MINOR	CO-PILOT	B52			low level ejection upwards		
31	3	MINOR	GUNNER	B52			low level ejection downwards		extremity
31	4	FATAL	EW	B52			low level ejection downwards	didn't complete ejection, IW water	multiple
31	5	FATAL	NAV	B52			unknown if ejected	missing	
31	6	FATAL	RADAR NAV	B52			unknown if ejected	missing	
32	1	FATAL	PILOT	F111			controlled flight into water	impact with water (in AC)	multiple
32	2	FATAL	WSO	F111			controlled flight into water	impact with water (in AC)	multiple
33	1	FATAL	PILOT	F4			inverted nose down spin,mid-air col	loss of cockpit integrity	multiple
33	2	FATAL	WSO	F4			inverted nose down spin,mid-air col	loss of cockpit integrity	multiple
33	3	NONE	PILOT	F4	12,000.00	200	60 nose down, level bank	none	none
33	4	NONE	WSO	F4	12,000.00	200	60 nose down, level bank	none	none
34	1	MAJOR	PILOT	F111			unrecoverable roll	hard landing of ejection pod	spine
34	2	MAJOR	WSO	F111			unrecoverable roll	hard landing of ejection pod	spine
35	1	MINOR	PILOT	F16	1,200.00	230	5-10 nose down, 3000 ft/min sink	EF or OCS	spine
36	1	MINOR	PILOT	A7	17,000.00		25 nose up, 60 right bank	hard landing	neck
37	7	FATAL	CREW	KC-135A			no ejection capability	IWG, FIRE	
37	12	FATAL	PASSENGERS	KC-135A			no ejection capability	IWG, FIRE	
38.1	1	FATAL	PILOT	A10			no attempt to eject	IWG, controlled flight into ground	multiple
38.2	1	FATAL	PILOT	A37			ejection 1.5 sec prior to impact	IWG, didn't complete eject sequence	multiple
38.2	2	FATAL	CO-PILOT	A37			no attempt to eject	IWG, didn't eject	multiple

Individual mishap records database

Number	Person	Injury	Position	Aircraft	Altitude	Speed	Attitude	Injury cause #1	Injury location
39	1	MINOR	COMMANDER	B1B	67	150	45 right bank, 24deg/sec roll	blow to head during PLF	head
39	2	MINOR	PILOT	B1B	64	150	30 right bank, 21deg/sec roll	PLF or ejection force	back
39	3	MINOR	OSO	B1B	63	150	13 right bank, 15deg/sec roll	EF or PLF	back
39	4	MAJOR	DSO	B1B	65	150	20 right bank, 18deg/sec roll, climbing	haulback, EF, PLF,?	spine
40	1	FATAL	PILOT	A-10A			no attempt to eject	hit cockpit, loss of integrity	multiple
40	2	MAJOR	PILOT	A-10A	500	225	out of control roll and tumble	fall from tree, EF, AC tumble,?	spine
41	1	MAJOR	CREW	MC130E			no ejection capability	IW water, thrown from AC	spine
41	8	FATAL	CREW	MC130E			no ejection capability	IW AC, controlled flight into water	multiple
41	15	FATAL	PASSENGERS	MC130E			no ejection capability	IW AC, controlled flight into water	multiple
42	1	MAJOR	WSO	F15	7,000.00	0	spin	EF	spine
42	2	MINOR	PILOT	F15	7,000.00	0	spin	unknown	back
43	1	MAJOR	WSO	F4	0	100	on ground	EF	spine
43	2	MINOR	PILOT	F4	0	100	on ground	dragged by chute	multiple
44	1	MAJOR	WSO	F4	2,000.00	460	rapid pitch& left roll	Ejection force	spine
44	2	NONE	PILOT	F4	2,000.00	460	rapid pitch& left roll	none	none
45	1	MAJOR	PILOT	F16	12,500.00	270	level	PLF- steep, rocky terrain	extremity
46	1	MAJOR	PILOT	F16	600	188	level	PLF - low eject, steep terrain	extremity
47	1	FATAL	PILOT	F111			excessive delay, eject rocket failed	IWG	multiple
47	2	FATAL	CREW	F111			excessive delay, eject rocket failed	IWG	multiple
48	1	MAJOR	PILOT	F16			hard landing	hard landing	spine
49	1	MAJOR	EWO	F4	4,800.00	220	70 nose down, 150 R bank, high sink	dragged by chute	extremity
49	2	MINOR	PILOT	F4	4,800.00	220	70 nose down, 150 R bank, high sink	WB, FLAIL	extremity
50	1	MINOR	PILOT	F4			stroke of seat triggered WSO eject	vibration, rapid deceleration	back
50	2	MAJOR	WSO	F4	0	50	stroke of seat triggered ejection	IWG/PLF/EF - hard eject, hard land	spine
51	1	MAJOR	PASSENGER	C5			aft section didn't catch fire	struck AC structure, thrown from AC	extremity
51	2	MAJOR	PASSENGER	C5			aft section didn't catch fire	seat fell from AC structure	spine
51	3	MAJOR	PASSENGER	C5			aft section didn't catch fire	hit cabin structure, fell from seat	thorax
51	4	NONE	CREW	C5			in loadmaster seat	tumble	
51	13	FATAL	3Pi,6C,4pa	C5				AC IWG, broke up, fire	
52	1	FATAL	PILOT-BKST	T38				AC roll during flight	head
52	2	MINOR	INSTRUCTOR	T38			Rode down landing	hard landing	

Individual mishap records database

Number	Person	Injury	Position	Aircraft	Altitude	Speed	Attitude	Injury cause #1	Injury location
53	15	FATAL	4crew,11passengers	CH3E			60 deg nose down, 20 deg right bank	IWG, immediate intense fire	multiple
54	1	MAJOR	CREW	T38	1,700.00	300	70 deg nose down, 210 deg left bank	chute struck riser	thorax
54	2	FATAL	PILOT	T38	2,500.00			chute didn't deploy, IWG	multiple
55	1	FATAL	PILOT	F16			caused mid-air collision	impact with canopy and debris	multiple
55	2	MAJOR	PILOT	F16	1,200.00	300	45 nose down, 45 left bank	EF, PLF, ?	spine
56	1	MINOR	PILOT	F4	5,300.00	150	60 right bank, 25 nose down, right spiral	EF, OCS, PLF, ?	neck
56	2	NONE	EWO	F4	4,500.00	150	60 right bank, 25 nose down, right spiral	none	none
57	1	FATAL	PILOT	F4	40	200	90 right bank	IWG prior to chute opening, out of envelope ejection	multiple
57	2	MAJOR	WSO	F4	50	200	60 right bank	EF	spine
58	1	MINOR	PILOT	F5	7,500.00	170	25 nose up, 5 left bank	broke through canopy, OCS	neck, spine
59	1	MINOR	PILOT	F16	2,000.00	120	20 nose up, level otherwise	EF/OCS/PLF/?	neck
59	2	MINOR	INSTRUCTOR	F16	2,000.00	120	20 nose up, level otherwise	EF/OCS/PLF/?	neck
60	1	MAJOR	PILOT	F16	0	50	on ground	EF (calculated 14.5 G)	spine
61	1	FATAL	PILOT	F4	600	150	30 nose down, 90 left bank, 17kft/min sink	*ejection too low/late*, IWG	multiple
61	2	MINOR	WSO	F4	900	160	30 nose down, 90 left bank, 17kft/min sink	EF - head turned to right	neck
62	1	MAJOR	PILOT	F106	3,200.00	200	45 nose down	PLF	spine
63	1	FATAL	PILOT	F4	290	300	20 nose up, 110 right bank, roll right	IWG, ejection too late	multiple
63	2	MAJOR	WSO	F4	245	310	20 nose up, 110 right bank, roll right	EF, felt back pain during descent	spine

Individual mishap records database

Injury location #1	Injury cause #2	Injury location #2	Seat type	Ejection position	Landing position	Hosp/ground	Number	Person
multiple lacerations and contusions	struck by night vision goggles	right orbit fx, mid-sternum fx				(in days)	1	1
multiple extreme						fatal	1	3
multiple extreme						fatal	1	9
15% T8 comp fx , 10% T7 comp fx			ACII	correct	hard, partially inflated canopy	indef	2	1
multiple extreme						fatal	3	1
none			ACII	correct	correct	none	4	1
multiple extreme			ACII			fatal	5	1
						fatal	6	5
							6	9
						fatal	6	11
T4, T5 anterior compression fx			MB	poor			7	1
right shoulder dislocation	FLAIL	non-displaced fx of right humerus	MB	unaware, "poor"			7	2
massive head injuries						fatal	8	1
45% T4 anterior compresssion fx			F111	didn't brace		?/90	9	1
facial laceration	PLF, did brace for impact	diffuse lower back strain	F111	braced			9	2
dental fx, perioorbital contusion	EF	acute low back strain	MB	correct			10	1
acute cervical strain	OCS	multiple contusions	MB	leaning forward with hands up			10	2
multiple extreme						fatal	11	1
multiple extreme						fatal	11	2
mutliple extreme						fatal	12	1
multiple extreme					impact with interior of AC, thrown	fatal	12	2
L elbow fx, L orbit fx					thrown clear		12	3
L scapula fx, sternum fx	*decelerative forces*	L1 compression fx, T1 transverse process fx			thrown clear		12	4
multiple extreme			MB			fatal	13	1
elbow contusions	PLF/IW trees on descent	abrasions, etc.	MB				13	2
multiple extreme						fatal	14	1
multiple extreme						fatal	15	8
hand lacerations			MB				16	1
15% compression fx of T7	loss of helmet	face and head abrasions	MB				16	2
multiple extreme						fatal	17	6
multiple extreme							18	6
							18	84
multiple extreme						fatal	19	1
multiple extreme w/burns						fatal	20	6
mild cervical strain			MB	optimal	correct		21	1
anterior compression fx of T8			MB	hips forward, feet 75% extended	correct		21	2
25% anterior compression of L1			ACII	hunched forward	ok		22	1

Appendix A-1

Individual mishap records database

Injury location #1	Injury cause #2	Injury location #2	Seat type	Ejection position	Landing position	Hosp/ground	Number	Person
L1 compression fx,T7 compression fx	PLF - hard landing in capsule	right leg fx, right eyebrow contusion	F111		70 deg. nose low capsule landing		23	1
unstable burst fx of L1	PLF - hard landing in capsule	abrasions and contusions	F111		70 deg. nose low capsule landing		23	2
15% anterior wedge fx of L1	OCS	contusions, abrasions around harness	ACII	head forward	soft earth, feet first,fell on face		24	1
hangman fx of C2, 3mm displacement of C3	PLF	right ankle sprain	ESCAP	head forward, OCS-head forward	poor	indef. gnd	25	1
avulsion fx spinous process of T1			MB	head and elbow fwd, unaware			26	1
abrasion			MB	correct, aware			26	2
20% compression fx of T12, 10% compression fx of L1			MB	correct	ok		27	1
50% compression fx of T12			MB	hips forward	ok		27	2
closed head injury, scalp laceration	seat tumbled, hit by debris	tear of long head of biceps	ACII	unknown, pilot amnesia	unknown, pilot amnesia	4/?	28	1
multiple extreme, multiple transection			MB				29	1
L1, T12 compression fx			MB	?	?	2/?	29	2
mild sprain L foot and hand	time spent in water	hypothermia					30	1
none							30	2
low back sprain, left knee sprain	impact with water (in AC)	right foot sprain, left wrist sprain					30	3
						fatal	30	4
perirenal hemotoma	impact with water (jumped from AC)	fx left dist radius, right retinal hemotoma				30/?	30	5
shoulder sprain							31	1
abrasions, contusions							31	2
finger injury on left hand							31	3
multiple extreme						fatal	31	4
						fatal	31	5
						fatal	31	6
multiple extreme						fatal	32	1
multiple extreme						fatal	32	2
multiple extreme						fatal	33	1
multiple extreme						fatal	33	2
none			MB	head forward			33	3
none			MB	arms up, forced leftwards in seat			33	4
50% T6 compression fx with canal injury			F111			45/?	34	1
T6,T7 compression fx	hard landing/separation of capsule	neck muscle strain	F111			45/?	34	2
paraspinal thoracic muscle sprain			ACII	head forward, correct otherwise	proper PLF	1 or 2	35	1
tenderness around C7	OCS	tongue laceration	ESCAP				36	1
						fatal	37	7
						fatal	37	12
multiple extreme						fatal	38.1	1
multiple extreme						fatal	38.2	1
multiple extreme						fatal	38.2	2

Individual mishap records database

Injury location #1	Injury cause #2	Injury location #2	Seat type	Ejection position	Landing position	Hosp/ground	Number	Person
concussion	landed on survival kit	bruised butt, lacerations, abrasions	ACb-1		almost flat on back	30/?	39	1
low back strain, bruised butt	PLF	left hand and arm contusions	ACb-1		not yet vertical	5/?	39	2
low back strain, bruised butt	PLF	abrasions, contusions	ACb-1		normal	10/?	39	3
L1 compression fx			ACb-1	leaning forward	normal	?/indef	39	4
multiple blunt trauma						fatal	40	1
L1 compression fx	ejected thru fireball	burns	ACII	tumbling	stuck in tree, dropped 15-20ft	major	40	2
L3,L4 right transverse process fx	IW water, thrown from AC	L2, L5 compression fx, left scapula fx				indef	41	1
multiple extreme						fatal	41	8
multiple extreme						fatal	41	15
25% T5 compression fx			ACII	hips lateral	?	?	42	1
lumbrosacral strain			ACII	?	?	?	42	2
10% T12 compression fx,	loose harness	shoulder abrasions	MB	unknown, no memory of ejection	unknown, no memory of landing	6/?	43	1
multiple abrasions			MB	unknown	dragged on ground	3/?	43	2
T12 anterior wedge compression fx	flail, windblast	comminuted fx of left humeral head	MB	out of position - unaware of ejection	face first in water	6/180	44	1
none			MB	correct body position initiated ejection	fell backwards in water	1/none	44	2
spiral fx of right tibia	PLF - steep, rocky terrain	spiral fx of right fibula	ACII	forward from seat back	fell forwards, looking down	6/indef	45	1
comminuted fx of tibia	PLF - low eject, steep terrain	2 fxs of fibula	ACII	correct body position	gusty, snow conditions	6/180	46	1
multiple extreme	IWG	multiple extreme	f111			fatal	47	1
multiple extreme	IWG	multiple extreme	f111			fatal	47	2
T11 and T12 compression fractures	hard landing	left rib fxs, right wrist sprain		didn't attempt ejection		?/170	48	1
hip, calf contusions	helmet flew off	lip, scalp abrasions and contusions	MB	leaned forward, arms up	proper PLF	1/none	49	1
right scapula displaced fx	WB, FLAIL	clavicular joint separation	MB	correct body, arms forward	fell backward, dragged in chute	1/45	49	2
back sprain/strain	vibration, rapid deceleration	contusions, abrasions				1/4	50	1
L3 explosion compression fx, T12 compression fx	IWG/PLF	leg, ankle, pelvic fxs	MB	head forward, arms up, unaware	looking down, fell backwards	30/540	50	2
tibia and fibula fxs at ankle		in shock				56/indef	51	1
L1 anterior compression fx	tumbled in cabin	contusions, abrasions				14/30	51	2
9th rib fx						14/30	51	3
abrasion/contusion						3/14	51	4
	blunt trauma, burns, smoke inhalation					fatal	51	13
broken jaw	out of envelope ejection	C5 avulsion, rib fx, skull fx, etc.	Nthp	injured, dazed, position unknown	hit ground in early deployment	fatal	52	1
abrasions and contusions						1/16	52	2

Appendix A-1

Individual mishap records database

Injury location #1	Injury cause #2	Injury location #2	Seat type	Ejection position	Landing position	Hosp/ground	Number	Person
8 fatal impact injuries, 7 fatal fire/smoke inhalation		blunt trauma, burns, inhalation				fatal	53	15
8,9,10 rib fx	PLF, ?	mild anterior wedge fx of L1	Nthp	proper	unconscious	6/7	54	1
multiple extreme			Nthp			fatal	54	2
multiple extreme						fatal	55	1
T11, T12 L1 compression fx			ACII	head, hips forward	fell back, fell on butt	6/150	55	2
cervical strain			MB	*head forward*	fell oblique, *muscles tense*	0/10	56	1
none			MB	correct position	correct position	0/7	56	2
multiple extreme			MB			fatal	57	1
L1 compression fx, lumbar strain	PLF	R calcaneus fx	MB	head and body forward, poor position,	tense, fell backwards	1/50	57	2
neck, thoracic stiffness			?	correct	correct	1/3	58	1
mild posterior neck muscle strain	torso harness straps	abrasion	ACII	correct	backwards	0/1	59	1
neck muscle strain			ACII	correct	correct	0/1	59	2
5% anterior compression L2, 25% anterior compression L4	EF, pre-existing injury	L-1, T-12 fxs	ACII	correct or torso slightly forward	correct	3/100	60	1
multiple extreme			MB			fatal	61	1
cervical strain	PLF	ankle sprain	MB	head turned to right, unaware	look down, fell backwards	unk	61	2
L3 *fx, unstable, neurological deficit*, L1 compression fx	IWG, PLF	avulsion *fx right arm*, hemotoma on butt	?	head up, body correct	fell bkwds, tense, hit butt, elbow	20/350+	62	1
multiple extreme			MB			fatal	63	1
10% T11 comp fx	PLF	torn knee ligament	MB	head forward	fell bkwds, tense	1/45	63	2

APPENDIX A-2
SUMMARY OF REVIEWED AIR FORCE SAFETY AGENCY (AFSA) MISHAP FILES

NOTE: Underlined numbers are Simula's reference numbers for the mishap files.

44 Spine fx, Arm fx; No Injury
MAJOR; NONE
Dual ejection from RF-4. Pilot, aware, okay. WSO was unaware and in poor body position (shoulders forward). MB seats. WSO: T12 anterior compression fx (EF). Comminuted fx of left humeral neck (FLAIL). 2,088' AGL. 459 KIAS. 10 deg nose up, 5 deg left bank (rolling), 1.3 Gz at ejection.

45 Leg fx
MAJOR
Ejection from F-16. Pilot GLOC'ed. Ejected at 11,000' AGL, 270 KIAS. Broke R leg on impact with terrain (big rock, 30 deg slope, twisted leg). R tibia - comminuted spinal fx in distal diaphysis w/1 cm disloc, R fibula non-displ fx. ACES II seat. Level ejection. PLF - fell fwd, looking down.

46 Leg fx
MAJOR
Ejection from F-16C. Broke leg on landing - steep, rocky terrain. 600' AGL, 188 KIAS. ACES II seat. Optimal ejection position. Wind gusts to 24 K. PLF - fell fwd with muscles tense.

49 Shoulder separation, scapula fx; contusions
MAJOR; MINOR
Dual ejection from F-4G. 4,800' AGL, 220 KIAS, 25K'/min sink rate. 60-70 deg nose down, 150 deg R bank (30 deg/sec roll). Out of control. MB Mark VII seats. MP: minimally displaced R scapula fx, clavicular joint separation. (WB, FLAIL). Dragged by chute, moderate OCS. MESO: contusions and abrasions from being drug by chute and from helmet coming off (loose strap).

48 Rib fx, spine fx, wrist sprain
MAJOR
Hard landing from F-16, high sink rate. No flight recorder. 50% T12 vert compression fx, from A/C initial impact (20-30 Gz), posterior T11 and T12 ribs, sprain R wrist.

47 Multiple extreme; Multiple extreme
FATAL; FATAL
F-111. 186 Knot ground speed, 20' AGL.
MP: rib, clavicle, scapula, sternum, L1, cervical, pelvic fractures.
MC: skull, rib, pelvic, T12/L1 fractures.
Insufficient time for ejection, ejection rocket misfire.

50 Back sprain; spine, femur, pevic, ankle fx
MINOR; MAJOR
MP problem on take-off, nose gear collapse, misfire of rear eject seat F-4E. A/C 20-25 deg nose down, 24 deg. L bank. MB seats. G est: .5x, 1y, 0z. MP: back sprain - vibration of riding out plane, or rapid deceleration. MWSO: L3 explosion compression fx, subtroch L femur fx, nondispl. pelvic fx, retroperitoneal hematoma, R and L calcaneal fx (PLF), T12 compression fx (EF - poor body position: head forward, arms up), anterior chest contusions (harness). Chute did not fully deploy. Unaware of impending ejection.

35 Thoracic sprain

MINOR

F-16 engine failure with a successful ejection. ACES II seat. 1,200' AGL, 230 KIAS, 3,000 ft/min sink. 5-10 deg nose down. Proper PLF, fell into bush head fwd resulting in mild paraspinal thoracic muscle sprain, believed to be from EF or possibly OCS.

51 Multiple Extreme; ankle fx, L1 fx, rib fx, none

13 FATAL; 3 MAJOR; 1 NONE

C-5A. Crash on take-off. Altitude peak at 73' AGL, left roll. 12 instant deaths (mostly massive blunt trauma). Of survivors, those at the back (rear-facing) fared the best since their section was separated and mostly clear of post-crash fire. Two sets of injuries occurred when seats fell from plane, as they were upside down when plane came to rest. Person non-injured was fwd-facing and furthest back in the plane. Energy absorption and lack of fire in the rear section was most helpful in those that survived.

53 Multiple extreme; fire

15 FATAL

CH-3E. Rotor blade failed. 20 deg R bank, 60 deg nose down, massive post-impact fire. 8 killed instantly from impact injuries, 7 had no or survivable injuries and were killed in the fire. Fwd deceleration was over 20 G (3 of 4 crew had fatal neck injuries, 4th had no NVG) 1 fatal neck injury in crew compartment related to NVG assembly. Summary: NVG may have exacerbated the situation but none would have survived the fire. Of those receiving injuries - proper positioning and restraints other than a lap belt (most passengers in side-facing seats) may have helped lessen the degree of injury. In the cockpit, the G forces were too extreme, airbags may have helped but the post crash fire most likely made the incident unsurvivable for the front occupants also.

52 Multiple extreme; abrasion/contusion

FATAL; MINOR

Pilot performed out-of-envelope ejection and was killed. Instructor rode down the crash and received only abrasions and contusions. Instructor abrasions/contusions related to hard landing. Pilot was in instrument hood. Ejection was self-initiated, may have already been injured from hitting hood during loss of control. Ulna fx - hand on ejection grip during AC roll. jaw fx - impact with left canopy. Avulsion fx of dorsal C5, multiple R and L rib fx. Comminuted skull fx. Additional IWG style injuries. 0 altitude ejection, little fwd movement. Chute did not deploy fully.

54 Rib fx, burn; multiple extreme

MAJOR; FATAL

Pilot lost control of T-38. Both crew ejected. Pilot fatal w/o chute deployment, unsurvivable IWG injuries. Crew eject 1,700' AGL, chute open 500', 300 KIAS. 70 deg nose down, 210 deg left bank. Crew - struck chute riser and fx left anterior 8, 9,10 ribs. Unconscious on landing. Mild anterior wedge fx of L1, may have been due to previous asymptomatic injury.

55 Multiple extreme; spine fx

FATAL; MAJOR

Mid-air collision of F-16's. Instructor P fatal - hit canopy and debris, craniocerebral injuries, c1 fx, internal deceleration injuries, massive internal injuries - dead on impact. Cockpit crushed by impact and by tail section collapsing into it.

MP - minimal T11, T12, and L1 compression fractures. Poor body position upon ejection, ACES II seat, nose down 45 deg, left bank 45 deg, head and hips forward upon ejection. Lap belt was loose. Injuries may have been exacerbated by impact prior to ejection.

61 Multiple extreme; ankle sprain, cervical strain
FATAL; MINOR
AC F-4C out of control. MP initiated dual ejection. MWSO ejected okay but MP too low approx. 600' AGL, 150 KIAS, 17,400 ft/min sink rate. 30 deg nose down, 90 deg left bank. Pilot hit ground prior to man/seat separation. Multiple extreme including skull fx, caudal cranial dislocation, C6 comp fx, rib and pelvic fx. MB MK-H7AF seat. MWSO - ankle sprain on PLF, cervical strain from improper head position during ejection. Gz 1-1.5. Head turned to right on ejection - unaware.

56 Neck sprain; none
MINOR; NONE
F-4 out of control on G awareness turn. Both ejected successfully over 4,000' AGL, 150 KIAS. Plane in right-hand spiral. MP - cervical sprain attributed to hyperflex/exten type of injury, head fwd on ejection initiated by WSO. WSO - no injury. MB seats. MP - 24 yo, WSO - 34 yo, but daily weight train. Seems like this was a good ejection with no injuries - sufficient altitude, decent body position, and healthy individuals.

57 Multiple extreme; spine, foot fx
FATAL; MAJOR
F-4 wing folded on take-off. Low ejection, WSO initiated. MP ejected during 90 deg right bank. IWG prior to seat separation. WSO - L1 anterior compression fx. Severe lumbar muscle strain. R calcaneus fx (PLF). MB Mark VII ejection seat. Back injury of questionable origin - assumed to be EF.

58 Neck/thoracic stiffness
MINOR
F-5E landing gear not lowered. Controlled ejection. Northrup seat. 7,500' AGL, 170 KIAS, aware, neck and thoracic stiffness from OCS since the pilot was looking at his lap belt when the chute opened.

59 Cervical strain; cervical strain
MINOR; MINOR
F-16D, controlled, successful ejection. MP - minor posterior cervical muscle strain. ACES II seat, 20 deg nose up, bad PLF - strain could have occurred on EF or PLF, young and healthy. IP - minimal posterior cervical muscle strain. Aware but felt hyperflex of neck upon ejection.

60 Spinal fx
MAJOR
F-16C problems on landing. Pilot ejected on ground. Initial impact of about 7 G. 5% anterior compression of superior surface of L2, 25% of L4, may have been pre-disposed because of prior L1-T12 injuries. Long, in-depth analysis with conclusion that injuries occurred with a 14.5 G force in the spine 4 deg fwd, aggravated by previous injury. ACES II seat. Ruled out impact and PLF as injury cause.

62 Spinal fx
MAJOR
F-106A (Convair) pilot GLOC'd, ejected, eject seat tangled after separation. Injuries due to excessive rate of descent. Severe unstable L3 fx with mild neuro deficit to R leg. Stable compression fx of L1. 3,200' AGL, 200 KIAS, rate of desc. est at 25-30 ft/sec. PLF - tense, fell hard on butt after feet.

43 Spinal fx
MAJOR; MINOR
Two F-4's involved but one landed safely with no injuries. The second landed short of the runway. WSO ejected unintentionally and suffered 10% T12 compression fx, laceration to right shoulder due to loose shoulder harness. WSO didn't remember ejection. 0 AGL, 100 KIAS. Pilot suffered abrasions as he was pulled from AC by his chute.

42 Spinal fx, lumbrosacral strain
MAJOR; MINOR
F-15D departed controlled flight, entered spin, ejection 7,000' AGL, 0 KIAS. WSO had 25% T5 fx (hips lateral on ejection); ACES II seat. Pilot - lumbrosacral strain from "ejection acceleration". WSO was 38, pilot 43.

28 Non-fatal head injuries, arm muscle
MAJOR
Pilot ejected from F-15 at 5,100' AGL, 200 KIAS, 45-60 deg. left (ac had already rolled four times), 40-60 deg. nose down. Ejection abnormal w/ seat tumbling due to severed drogue chute, lost helmet due to loose chin strap. Pilot suffered closed head injury, scalp laceration and biceps muscle tear. ACES II seat. Injuries result of tumbling seat and hitting ac or debris. Pilot suffered amnesia of the incident.

29 Spinal fx; multiple extreme
MAJOR; FATAL
Aircraft caught fire with explosion on low-level mission. WSO eject successful, pilot didn't complete ejection sequence - fatal. 25% fx of L1, also T12. WSO initiated. Pilot multiple extreme incl. brainstem and spinal cord transection. 300' AGL, 300 KIAS, 13K ft/min sink, nose up 5 deg, est 1 Gz.

30 Various sprains, radius fx, 1 fatal(missing)
MINOR; NONE; MINOR; MISSING; MAJOR
Controlled ditching of MH-60G into sea. 5 people involved. Pilot - minor: left foot and hand sprains; Co-pilot jumped from ac prior to ditch, NONE; Flight Engineer sitting on floor when ditched, sprains of low back, left knee, right foot, left wrist due to impact with water; Rescueman missing as he exited AC prior to ditching; Rescueman2 exited prior to ditching, fell 60' impact with water, perirenal hemotoma, other hemorrhages, L dist rad fx from holding lift raft.

31 Shoulder sprain; 2 minor; 1 fatal; 2 missing
3 MINOR; 1 FATAL; 2 MISSING
B-52 with 6 people. Pilot: survived with minor shoulder sprain. Low ejection upwards. Copilot: survived with minor abrasions. Low ejection upwards. Gunner: survived with minor finger injury. Low ejection down. EW: didn't complete ejection sequence. Fatal impact with water or with debris. Blow to face/head. NAV: missing. Radar NAV: missing.

32 2 Multiple extreme
FATAL; FATAL
F-111 impacted with water without ejection. "Controlled flight into water". Both suffered brain avulsions due to impact with glare shields, flail chest, etc.

33 2 multiple extreme; 2 no injury
FATAL; FATAL; NONE; NONE
2 F-4's. AC1 cockpit integrity was lost in crash. Crew killed during this impact. AC2 crew ejected successfully. MB seats. WSO (28 yo) was out of position laterally but had no injuries. Pilot no injuries even though his head was flexed forward. (29 yo). 12,000' AGL, 200 KIAS, 6,000 ft/min sink, 60 deg nose down, yaw rate, 6-8 deg, est 4 Gy.

34 Spinal fx; spinal fx
MAJOR; MAJOR
F-111D lost control, unrecoverable roll, module "landed hard" Pilot: 34 yo, T6 50% compression fx. WSO: T6 compression fx, T7 compression fx, strained neck muscles. Descent may have been up to 32 ft/sec which would allow the 20-30 G impact that the report claims to be necessary for compression fx of thoracic vertebra. Capsule landed aft and left.

36 Spinal sprain
MINOR
A-7 lost controlled flight, pilot ejected 25 deg nose up 61 deg right bank. Abrasions from chute risers, tongue bite during OCS, C7 tenderness from PLF on hard surface. ESCAPAC ejection seat.

37 19 fatalities
FATAL
Massive blunt force trauma and burns. KC-135A crashed on take-off at critical gross weight. All fatal, unsurvivable.

38A Multiple extreme
FATAL
A-10A. Controlled flight into ground because of distraction in cockpit. No attempt to eject, multiple extreme injuries.

38B 2 Multiple extreme
FATAL; FATAL
A-37B. Pilot ejected 1.5 sec prior to impact. Pilot didn't complete ejection sequence; Right seat didn't attempt ejection. Massive blunt traumas.

39 Contusions, etc, back strain, spinal fx
MINOR; MINOR; MINOR; MAJOR
B-1B too low on landing, clipped poles and lost control. ACES B-1 seats. Commander: 67' AGL, 150 KIAS, 45 deg right bank, 24 deg/sec roll, landed almost flat on back, concussion, mult. lacerations. Pilot: 64' AGL, 150 KIAS, 30 deg right bank 21 deg/sec roll, minor contusions, etc. OSO: 63' AGL, 150 KIAS, 13 right bank, 15 deg/sec roll, low back strain, minor abrasions, unaware of ejection. DSO: 65' AGL, 150 KIAS, 20 right bank, 18 deg/sec roll, compression fx of L1 (L1-T12 fusion), may have been leaning far forward at start of ejection sequence.

40 Multiple extreme; Spinal fx
FATAL; MAJOR
Midair collision of 2 A-10A. AC1 pilot fatal - multiple blunt trauma and penetration from cockpit crush. AC2 pilot ACES II intentional ejection. 200-250 KIAS, L1 compression fx may have been due to tumbling aircraft or ejection or fall from tree on landing. 33 yo. 500' AGL, fell 15-25' from tree.

41 Spinal fx, shoulder fx, knee fx
9 crew, 15 passengers - only 1 crew survived (MAJOR).
MC-130E controlled flight into water. Survivor thrown from AC upon impact (not sure how). L3 and L4 right transverse process fx, L2 and L5 compression fx, fx left scapula and left patella. 28 yo.

8 Multiple extreme
FATAL
F-15 impacted side of mountain. Pilot suffered massive head injuries from impact with canopy. No attempt at ejection.

1 Multiple extreme; Minor
12 FATAL; 1 MINOR
HH-60G controlled flight into water. 3 crew and 9 pax never noticed and were killed on impact. Impact force greater than 60 G. Most lost helmets and vests on impact, considered non-survivable. Pilot and co-pilot thrown clear, but co-pilot struck by main rotor blade. Multiple abrasions and lacerations from debris. R orbit fx from NVG.

2 Spinal fx
MAJOR (classified as minor but I disagree)
F-16A lost thrust. Ejection. ACES II seat. 50' AGL, 175 KIAS, 5 deg nose up, 20 deg right bank, 15% T8 compression fx, 10% T7 compression fx, cause either ejection or landing fall. Pilot aware and in correct position. Chute streamed and didn't fully open so might be more likely a PLF injury.

3 Multiple extreme
FATAL
U-2R controlled turn progressed into spiral. Attempted ejection 450' AGL, 124 KEAS, 30 deg bank, nose down 80 deg, roll 50 deg/sec, sink 12K ft/min, G est 150-200 x and y. Chute did not open. Multiple ground impact injuries.

18 6 fatal
6 FATAL, 84 civilian injuries.
A-10A crash into populated area. No attempt to eject. Multiple extreme injuries and much civilian damage.

26 Spinal fx, abrasions
MAJOR; MINOR
F-4 out of control. 2 successful ejections. MB seats. Ejection initiated by WSO, pilot unaware. Below 3,000' AGL, 225 KIAS, pilot (30 yo): head and elbow fwd, small avusion fx spinour process T1 - out-of-position EF injury; WSO: abrasions only from chute deployment.

11 Multiple extreme; multiple extreme
FATAL; FATAL
F-15E impacted with ground. Both fatal, massive blunt force traumas.

22 Spinal fx
MAJOR
A-10A engine failure on takeoff. Successful ejection. 140' AGL, 132 KIAS, 12 deg nose down, 15 deg right bank. 40 yo. hunched fwd, 25% anterior compression of L1. Injury probably exacerbated by pilot age. ACES II seat.

4 No injury
NONE
Ejected from F-16A after problem with takeoff. Proper position 900' AGL, 190 KIAS, L bank 30 deg. ACES II seat.

21 Cervical strain; spinal fx
MINOR; MAJOR
F-4E lost power. 2 successful ejections. 500' AGL, 220-250 KIAS, MB seats. Pilot: optimal position, mild R cervical muscle strain (EF) 40 yo, WSO: hips fwd, legs only partially extended; anterior compression fx of T8 caused by G loading of spine at distal thoracic kyphosis/lumbar lordosis transition zone. Long trunk height (22 in.).

27 Spinal fx; spinal fx
not categorized (MAJOR, MAJOR)
F-4C failed to recover from stall, two crew ejected successfully at 1,050' AGL, 210 KIAS. Pilot (31 yo) - had 20% comp fx of T12 and 10% fx of L1. He recalls a sharp pain on PLF but he was unaware of ejection so neither cause can be ruled out, hip position unknown during ejection. Back pilot (30 yo) - 50% compression fx of T12. Hips forward during ejection. MB seats, level ejection.

17 Multiple extreme (6)
6 FATAL
HH-3E crashed into a ridge, exploded and impacted the backside of ridge. Four crew and two passengers received fatal injuries. 100-200 G impact and complete intrusion into cockpit made this an unsurvivable accident. Pilot and co-pilot thrown from craft and received multiple head inj., others received massive blunt force trauma.

25 Cervical fx; ankle sprain, contusions
MAJOR
A7-D pilot ejected after engine lost power at 1,000' AGL, 17.5 AOA, R wing down, 230 knots. Pilot initiated ejection but in poor position for chute opening. Hangman's fx C2, 3 mm anterior dislocation of C3 from OCS, R ankle sprain on PLF, contusions. Head out of position for OCS, forced neck into hyperextension. 29 yo - indefinite grounding. Ejection seat (ESCAPAC 1C-2) rotating prior to man/seat separation.

5 Fatal head injuries
FATAL
F-16 pilot ejected shortly after takeoff (spatial disorientation?) 32 yo, prior hosp for back problem (w/o notification of flight surgeon). During seat separation, the chute risers contacted the seat structure, causing entanglement. Pilot struck in head and fatally injured during entanglement.

24 Spinal fx, contusions, etc.
MAJOR
A-10A departed controlled flight, pilot ejected at 400' AGL, 45 deg nose low, 90 deg R bank, 160 knots. Pilot (28 yo) head fwd on eject, landed feet then face on soft earth. Stable L1 comp fx, 15% with anterior wedging probably caused by PLF. Harsh OCS but only seemed to product abrasions/contusions. ACES II seat.

19 Massive blunt force trauma
FATAL
A-7D hit ridge, no eject attempt, massive blunt force trauma incl. subtotal decapitation and brain avulsion.

14 Massive impact trauma
FATAL
F-15 entered L turn with enough G to fail wings. No eject attempt. Impacted water. Massive injuries including spinal transection.

7 Spinal fx; shoulder fx
MAJOR; MAJOR
F-4C engine problems, 2 eject at 9,000' AGL, 90 deg L bank, 20 pitch down, 320 KIAS, WSO unaware. Neither in optimal position. Pilot (35) - anterior compression fx of T4 and T5 by improper eject position. WSO (31)-R shoulder dislocation, R humerus fx by flailing - windblast inj. MB seats.

20 Multiple extreme; burns
6 FATAL
C-130E. Six fatal crew. Departed controlled flight on approach. Impact and post-crash fire made crash non-survivable.

10 Back strain; back strain
MAJOR; MINOR
F-4C lost control after roll, dual eject. 1,800-2,300' AGL, 45-60 deg nose low, 60 deg bank. MP - optimal position, aware, 41 yo, dental fx due to helmet coming off, low back strain prior low back fx. Passenger - 30 yo acute cervical strain by ejection, was leaning fwd on eject. MB seats.

9 Spinal fx; back strain
MAJOR; MINOR
F-111F in-flight fire; ejection. Pilot did not brace for impact and suffered anterior compression fx of T4 (45%) caused by ground impact. Pilot 31 yo. WSO (24 yo.) - braced for impact. Lacerations, low back strain w/no other symptoms. "Older rate-independent seat cushions were in place. Newer rate-dependent cushions shown to decrease Gz."

13 Multiple extreme; minor
FATAL; MINOR
F-4 lost control. Pilot did not eject in time and impacted prior to man/seat separation. WSO - 31 yo, 800' AGL, 45 deg right bank, 50 deg nose down (Pilot eject 500' AGL). Elbow contusion from flail. MB H7AF. WSO came down through trees and into ravine which was difference between his ejection and pilot's.

16 None; spinal fx
MINOR; MINOR
F-4C loss control, crew eject 3,000' AGL. Pilot lacerations only. 26 yo. WSO 15% compression of T7 from EF. WSO initiated ejection. WSO able to climb down 30' tree after inj. MB seats.

23 Spinal fx; spinal fx
MAJOR; MAJOR
F-111 ejection okay but failure of forward repositioning cable had capsule impact 70 deg. nose low, 2,400' AGL eject. Pilot - 29 yo, stable L1 comp fx and T7 (<50%). R medial epicondyle chip fx. WSO - 24 yo, overweight (215 lb 5'9"). Unstable burst fx of L1 by landing impact. Weight probably contributed to injury severity. "The failure of the forward repositioning cable contributed greatly... of over 100 successful ejections in F-111, approx. 33% sustain thoracic fracture...normal G force is 16-25 G but with impact conditions, this situation was probably more"

15 Multiple extreme
8 FATAL
C-141B struck trees. Occupiable space gone, AC burned. Gx=80-100 for 3 victims, 30-50 for 5 others. Pilot and co-pilot impacted console, others all died of massive head/chest blunt force. 6 of 8 had extensive thermal injuries not related to cause of death.

6 Multiple extreme
5 crew, 11 civilians on ground fatal, 9 civilians injured on ground
C-130B crashed into restaurant and burned. >200 G impact. Non-survivable situation.

12 Multiple extr; multiple extreme; spine/shoulder fx; spinal fx
2 FATAL; 2 MAJOR
UH-1N crashed 12 deg nose high, 18 deg right bank, nose yaw left. Vz=40f/s, Vx=46 knots. AC bounced and rolled right, landed on its top.
Pilot - 26 yo. Spinal avulsion. First suffered major whiplash injury followed by severe hyperflexion when ac landed on its top, which severed the cord - instant death.
Co-pilot - L elbow fx, orbit fx. Thrown clear when seat harness popped during roll.
Engineer - 30 yo. Macerated spinal cord from secondary impact with terrain. Other injuries from being thrown around cabin and out cargo door. Hit head somewhere hard enough to destroy helmet.
Mechanic - 35 yo. l scapula fx, sternum fx, comp L1 fx, fx transverse process of T1, abdominal wall tear. Mechanic thrown out of craft but survived. Spinal fx attributed to vertical decelerative forces, but crash was so involved it is hard to ascertain.

63 Multiple extreme; spinal fx
FATAL; MAJOR
Low-level ejection from F-4. WSO suffered a spinal compression fracture (10% of T11), which he felt on chute descent, so it probably occurred from ejection forces. He also suffered R knee ligament tears from PLF. 245' AGL, 310 KIAS. Pilot suffered multiple extreme injuries, 290' AGL, 300 KIAS. Hit ground prior to chute opening.

APPENDIX B
INJURY MECHANISMS

The following table contains definitions of the injury mechanisms for the cervical spine. Also provided is an indication of the directions of loading necessary to produce the injuries.

Mechanism	Definition	Direction
	NOTE: Injury mechanisms defined in terms of the loading at the motion segment.	
Extension Teardrop Fracture	Avulsion fracture of the anterior aspect of vertebra, results from the pull of the ALL. Ejection injury. Hyperextension injury. In general population, this injury is most common in older patients with osteopenia.	Extension, combined loading with compression or tension
Flexion teardrop fracture	Characterized by complete disruption of all ligaments and the intervertebral disk at the level of injury, by disruption of the interfacetal joints, and by a large triangular fragment forming the anterior angle of the vertebral body. (Reference 26)	Flexion, compression with flexion
	Hyperflexion injury. The most devastating flexion injury since it is associated with immediate, complete paralysis with hypesthesia and hypalesthesia to the level of the lesion. (Reference 26)	
Pillar fracture	A vertical fracture of the articular pillar (mass) resulting from an impaction of the involved mass by the ipsilateral superior articular mass during hyperextension and rotation. (Reference 26)	Extension (Hyperextension) with rotation
Jefferson Fracture	Fracture of the arch of C1. Can be fatal. Seen with less than 1 cm of eccentric loading. The downward-driven occipital condyles act as a wedge, causing the C1 ring to spread and burst apart.	Compression, compression with extension
	The Jefferson fracture is a particular type of four-part atlas fracture. Other types of upper cervical compression fractures are sometimes also called Jefferson fractures.	
Wedge Fracture	Collapse of the vertebral body, usually C5-T1, often clinically benign when there is no compression of the soft tissue and no vertebral displacement. Anterior wedge fracture occurs with 1 cm or more of eccentricity.	Flexion, Lateral bending, compression with flexion, compression with eccentricity
	Pain can persist but injury is recoverable. Wedge fractures can occur even at relatively low loads but are often clinically benign.	
Burst Fracture	Can cause neurological damage when bone segments enter spinal canal. Often to C4-C6 in compression. Can be fatal.	Compression, compression with flexion
	A comminuted fracture of the vertebral body with variable retropulsion of the posterior body fragments into the spinal canal.	

Hangman's Fracture (traumatic spondylolisthesis)	Occurs when head impacts windshield or when extension moment is applied to upper cervical spine. Injury to C2 in which the pars interarticularis is fractured.	Extension, compression with extension, tension with extension
	Results from a separation of the anterior and posterior elements of C2 and also disrupts the C2-C3 disc.	
Fracture Dislocation	Generally occurs in high-magnitude combined-loading situations. The occurrence is dependent upon the magnitude of the posterior-anterior force. Occurs with 1 cm or more of eccentric loading. (Reference 27)	Compression with extension, compression with flexion
Whiplash Injuries	Occurs with rapid bending of the neck, producing tensile and compressive loads. Muscles, ligaments and joints affected. Non-contact soft tissue injuries in general.	Flexion/Extension bending, with compression or tension
Multipart axis fracture	Multiple fracture of the C1. Often fatal.	Compression
Hyperflexive strain (Anterior subluxation)	Hyperflexive strain is a temporary or partial luxation of the intervertebral joints following traumatic hyperflexion under moderate forces, including rupture of the PLL and joint capsule, often results in dislocation.	Compression with flexion, flexion, tension with flexion
Bilateral facet dislocation (locked vertebra)	Injury may include displacement of caudal facets of superior vertebra and extensive ligament disruption (interspinous, intertransverse, capsular, ligamenta flava, and annulus). Often an inertial injury.	Flexion, extension, tension, compression, rotation, or a combination of the above.
	Dislocation of each interfacetal joint at the same level. C2 to C7. The inferior facets of the dislocated body lie anterior to the superior facets of the subadjacent body. Fragments from impaction are generally of little clinical significance.	
Coal (Clay) Shoveler's fracture	Isolated fracture of the spinous process of C6, C7, or T1. Whiplash motion of the head with avulsion of the spinous process. The injury mechanism is disputed, however.	Flexion
	Occurs when head and upper cervical segments are forced into flexion against the opposing action of the interspinous and superspinous ligaments.	
Unilateral interfacetal dislocation	Dislocation of a facetal joint at one level on the side opposite that of the direction of rotation. The dislodged articular mass is displaced anterior to the subadjacent mass and becomes wedged in the inferior portion of the intervertebral foramen.	Compression with flexion, flexion, lateral bending, tension with flexion, rotation with flexion
	The posterior ligament complex and the capsule of the dislocated facetal joint are disrupted. The anterior and posterior longitudinal ligaments are disrupted.	

Hyperextension sprain or strain (hyperextension dislocation)	Disruption of the anterior longitudinal ligament, horizontal disruption of the intervertebral disk, or avulsion of the inferior end plate of the centrum from the superior margin of the disk. Often the cervical cord is pinched.	Extension
	Usually a result of a direct posterior force impacting on the face, propelling the head and cervical spine into hyperextension.	
Odontoid fracture (dens fracture)	Fracture of the dens. A particle can break off and effect the spinal cord (20-35%). Potentially lethal injury. The overall mechanism is poorly understood.	Flexion, horizontal shear
Occipitoatlantal dislocation	Fatal injury. Any separation of the craniovertebral joint; combination of either anterior or posterior displacement with distraction.	Tension
Compression fracture	Destruction of the bony centrum with loss of disk height, vertebral end-plate fracture with vertical herniation of the nucleus pulposus into the centrum. (Reference 8)	Compression, combined loading with compression
	Fracture can occur from C2 to T1, but it is most likely to occur in C4 to C6.	
Atlantoaxial dislocation	Injury may result in an occipital condyle fracture. Rotation itself is seldom enough to produce this injury.	Rotation, rotation with flexion, rotation with extension

APPENDIX C
EXPERIMENTAL LITERATURE DATABASE

The following database contains summaries of the experimental literature used to develop the neck injury criterion. A separate reference section corresponding to the literature in this database is included.

Appendix C

	Reference	Specimen	Subject Description	# Subjects	Load Description	Load key
1	Maiman et al. 1983	iso cerv s	Isolated Cervical Spine	5	Load applied to skull vertex by hydraulic piston, Lower cervical spine restrained	Compression
2	Roaf, 1960	iso cerv s	2 vertebrae with disc			Compression
3	Roaf, 1960	iso cerv s	2 vertebrae with disc			Compression
4	Messerer, 1880	iso cerv s	Single vertebra, dry, lower section		Compressive breaking loads	Compression
5	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, all	16	5 mm/sec	Compression
6	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, all	16	5 mm/sec	Compression
7	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, low	8	5 mm/sec	Compression
8	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, mid	8	5 mm/sec	Compression
9	Yamada, 1973	single ver	Single vertebra, wet			Compression
10	Yamada, 1973	single ver	Single vertebral disk, age 40-59			Compression
11	Yamada, 1970	iso cerv s	Cervical vertebra			Compression
12	Yamada, 1970	iso cerv s	Cervical disk			Compression
13	Moroney et al., 1988	iso cerv s	Intact 2 vertebral segments	16	35 segments from 16 cadavers, unembalmed, "low load rate, low load magnitude"	Compression
14	Culver, 1978	whole cad	Whole cadaver	8	9.9 kg padded impactor, cadaver supine, crown impact, lordotic curvature maintained	Compression
15	Culver, 1978	whole cad	Whole Cadaver		9.9 kg padded impactor, cadaver supine, crown impact	Compression
16	Panjabi, 1986	iso cerv s	Single motion segment		50 N max load, 9.7 N pre-load, "low load rate, low load magnitude"	Compression
17	Liu et al., 1982	iso cerv s	2 adjacent vertebrae, mid			Compression
18	Liu et al., 1982	iso cerv s	2 adjacent vertebrae, low			Compression
19	Liu et al., 1982	iso cerv s	Functional spinal unit			Compression
20	Sances et al., 1982	iso cerv s	Isolated cervical spines		Quasi-static compression failure	Compression
21	McElhaney et al., 1983	iso cerv s	Cervical spine, unembalmed,42-73yo, ligaments intact	14	Variable rate constant velocity tests 0.127 - 64 cm/sec, 200 N pre-load, lordotic curvature retained	Compression
22	McElhaney et al., 1983	iso cerv s	Cervical spine, unembalmed,42-73yo, ligaments intact	14	Constant velocity tests, load to failure, 64 cm/sec, 200 N pre-load, lordotic curvature retained	Compression
23	McElhaney et al., 1983	iso cerv s	37 yo, male, ligaments intact	1	50 cm/sec, max load 5340 N, max deflection 3.0cm, 200 N pre-load, lordotic curvature retained	Compression

	Reference	Specimen	Subject Description	# Subjects	Load Description	Load key
24	McElhaney et al., 1983	iso cerv s	49 yo, female, ligaments intact	1	50 cm/sec, max load 4860 N, max deflection 3.0cm, 200 N pre-load, lordotic curvature retained	Compression
25	McElhaney et al., 1983	iso cerv s	70 yo, male, ligaments intact	1	54 cm/sec, max load 5010 N, max deflection 2.9cm, 200 N pre-load, lordotic curvature retained	Compression
26	McElhaney et al., 1983	iso cerv s	41 yo, male, ligaments intact	1	45 cm/sec, max load 5270 N, max deflection 2.5cm, 200 N pre-load, lordotic curvature retained	Compression
27	McElhaney et al., 1983	iso cerv s	77 yo, male, ligaments intact	1	57 cm/sec, max load 3650 N, max deflection 2.7cm, 200 N pre-load, lordotic curvature retained	Compression
28	McElhaney et al., 1983	iso cerv s	64 yo, female, ligaments intact	1	92 cm/sec, max load 4060 N, max deflection 4.5cm, 200 N pre-load, lordotic curvature retained	Compression
29	McElhaney et al., 1983					Compression
30	McElhaney et al., 1983					Compression
31	Nightingale et al., 1991	iso cerv s		6	full constraint, inferior end-allow translation on vertical axis, quasi-static	Compression
32	Wismans et al., 1986	volunteer	NBDL data			Compression
33	Mouradian et al,	iso cerv s	C1-C2 sections		load through occiput, occiput and C2 embedded in epoxy	Compression
34	Mouradian et al.,	iso cerv s	C1-C2 sections		load through occiput, occiput and C2 embedded in epoxy	Compression
35	Mouradian et al.,	iso cerv s	C1-C2 sections		load through occiput, occiput and C2 embedded in epoxy	Compression
36	Bauze and Ardran, 1978	iso cerv s	Whole cervical spines	14	Constrain superior end in rotation,subject constrained inferiorly with pin, wanted bilateral locked facets	Compression (Eccentric)
37	Pintar et al., 1989	iso cerv s	Head/neck complex	7	loaded to failure at const deformation of 2mm/sec quasi-static, failure defined as a drop in force vs time trace	Compression (Eccentric)
38	Pintar et al., 1990	iso cerv s	Skull to T2	6	natural lordosis removed, axis aligned w/padded impactor, impactor rates 9.7 to 26.7 ft/sec	Compression (Eccentric)
39	Alem et al., 1984	whole cad	Whole cadaver	8	Impulse, 10 kg impactor, direction and padding varied, 7-11 m/sec	Compression (Eccentric)
40	Alem et al., 1984	whole cad	Whole cadaver	5	non-injurious neck impacts	Compression (Eccentric)
41	Hodgson et al., 1980	whole cad	Whole cadaver		Crown impacts from 121lb tackling block, helmeted heads, gripping action of block restricted head rotation	Compression (Eccentric)
42	Nusholtz et al., 1981	whole cad	Whole cadaver, unembalmed	12	Crown impacts, with padded impactor, 56 kg, pre-impact velocity 4.6-5.6 m/s	Compression (Eccentric)

	Reference	Specimen	Subject Description	# Subjects	Load Description	Load key
43	Nusholtz et al., 1983	whole cad	Whole cadaver, unembalmed, 51-70yo	8	Crown impacts, free fall drop tests from .8 - 1.8m, head impact forces varied from 3.2-10.8N	Compression (Eccentric)
44	McElhaney et al., 1983	iso cerv s	44 yo, male, ligaments intact	1	88 cm/sec, max load 5470 N, max deflection 4.4cm, 200 N pre-load, lordotic curvature retained	Compression (Eccentric)
45	McElhaney et al., 1983	iso cerv s	63 yo, female, ligaments intact, small segment	1	87 cm/sec, max load 3000 N, max deflection 2.8cm, 200 N pre-load, lordotic curvature retained	Compression (Eccentric)
46	Nightingale et al., 1991	iso cerv s		6	rotation constraint, inferior end-allow translation on vertical axis, quasi-static	Compression (Eccentric)
47	McElhaney et al., 1988	iso cerv s	Cervical spine		inferior end not allowed to rotate, constant velocity (quasi-static), eccentric	Compression (Eccentric)
48	Yoganandan et al., 1986	whole cad	Whole cadavers	16	Crown impact, dropped on head	Compression (Eccentric)
49	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, low	8	5 deg/sec	Extension
50	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, mid	8	5 deg/sec	Extension
51	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, all	16	5 deg/sec	Extension
52	Shea et al., 1991	iso cerv s	3 adjacent vertebrae,all	16	5 deg/sec	Extension
53	Moroney et al., 1988	iso cerv s	Intact 2 vertebral segments	16	35 segments from 16 cadavers, unembalmed	Extension
54	Maiman et al., 1983	iso cerv s	Isolated Cervical Spine	1	Load applied to skull vertex by hydraulic piston, 25 deg. pre-extended	Extension-compression
55	McElhaney et al., 1983	iso cerv s	58 yo, male, ligaments intact	1	50 cm/sec, max load 3560 N, max deflection 3.0cm, 200 N pre-load, lordotic curvature retained	Extension-Compression
56	McElhaney et al., 1983	iso cerv s	52 yo, male, ligaments intact	1	50 cm/sec, max load 4190 N, max deflection 3.0cm, 200 N pre-load, lordotic curvature retained	Extension-Compression
57	McElhaney et al., 1983	iso cerv s	62 yo, female, ligaments intact, small segment	1	84 cm/sec, max load 1930 N, max deflection 4.0cm, 200 N pre-load, lordotic curvature retained	Extension-Compression
58	McElhaney et al., 1983	iso cerv s	62 yo, male, ligaments intact	1	55 cm/sec, max load 3120 N, max deflection 3.0cm, 200 N pre-load, lordotic curvature retained	Extension-Compression
59	McElhaney et al., 1983	iso cerv s	46 yo, female, ligaments intact	1	56 cm/sec, max load 960 N, max deflection 2.9cm, 200 N pre-load, lordotic curvature retained	Extension-Compression
60	Shea et al., 1991	iso cerv s	3 adjacent vertebrae,lower	8	5 deg/sec	Flexion
61	Shea et al., 1991	iso cerv s	3 adjacent vertebrae,mid	8	5 deg/sec	Flexion
62	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, all	16	5 deg/sec	Flexion
63	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, all	16	5 deg/sec	Flexion
64	Moroney et al., 1988	iso cerv s	Intact 2 vertebral segments	16	35 segments from 16 cadavers, unembalmed	Flexion

	Reference	Specimen	Subject Description	# Subjects	Load Description	Load key
65	Liu et al., 1982	iso cerv s	Functional spinal unit			Flexion
66	Maiman et al., 1983	iso cerv s	Isolated Cervical Spine	4	Load applied to skull vertex by hydraulic piston, 25 deg. pre-flexed	Flexion-compression
67	Sances et al., 1982	iso cerv s	Isolated cervical spines		dynamic flexion-compression failures	Flexion-Compression
68	McElhaney et al., 1983	iso cerv s	46 yo, male, ligaments intact	1	50 cm/sec, max load 4720 N, max deflection 3.0cm, 200 N pre-load, lordotic curvature retained	Flexion-Compression
69	Nightingale et al., 1991	iso cerv s			unconstrained, inferior end-allow translation on vertical axis, quasi-static	Flexion-Compression
70	McElhaney et al., 1988	iso cerv s	Cervical spine	4	superior and inferior ends free to trans vertic and rotate saggitally, constant velocity (quasi-static), eccentric load	Flexion-Compression
71	Moroney et al., 1988	iso cerv s	Intact 2 vertebral segments	16	35 segments from 16 cadavers, unembalmed	Lateral Bending
72	Bowman et al., 1984	volunteer	Volunteer test sled data NBDL		treating cervical spine as pinned joints	Lateral Bending
73	Bowman et al., 1984	volunteer	Sled data from NBDL			Lateral Bending
74	White and Panjabi, 1990	iso cerv s	C0-C1 section			Range of Motion
75	White and Panjabi, 1990	iso cerv s	C1-C2 section			Range of Motion
76	Lysell et al., 1969	iso cerv s				Range of Motion
77	Schneider et al., 1975	volunteer	Volunteer, age 18 to 24			Range of Motion
78	Schneider et al., 1975	volunteer	Volunteer, age 62 to 74			Range of Motion
79	Yamada, 1970	iso cerv s	Cervical disk			Rotation
80	Moroney et al., 1988	iso cerv s	Intact 2 vertebral segments	16	35 segments from 16 cadavers, unembalmed	Rotation
81	Bowman et al., 1984	volunteer	NBDL data			Rotation
82	Goel et al., 1991	iso cerv s	C0-C1-C2 section		pure right axial rotation, 4 deg/sec	Rotation
83	Goel et al., 1991	iso cerv s	C0-C1-C2 section		pure right axial rotation, 50 deg/sec	Rotation
84	Goel et al., 1991	iso cerv s	C0-C1-C2 section		pure right axial rotation, 100 deg/sec	Rotation
85	Goel et al., 1991	iso cerv s	C0-C1-C2 section		pure right axial rotation, 400 deg/sec	Rotation
86	Wismans and Spenny, 1983	volunteer	Volunteer			Rotation
87	Cheng et al., 1982	whole cad	Whole cadaver, unembalmed	6	distributed frontal load to the chest - employed air bag, sled decelerations of 32 to 39g	Shear

Appendix C

	Reference	Specimen	Subject Description	# Subjects	Load Description	Load key
88	Fielding et al., 1974	iso cerv s	C1-C2 sections	20	perpendicular force applied, purpose was to rupture the transverse ligament	Shear
89	Fielding et al., 1974	iso cerv s	C1-C2 sections		perpendicular force applied, purpose was to rupture the transverse ligament	Shear
90	Fielding et al., 1974	iso cerv s	C1-C2 sections		perpendicular force applied	Shear
91	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, all	16	5 mm/sec	Shear-anterior
92	Shea et al., 1991	iso cerv s	3 adjacent vertebrae,lower	8	5 mm/sec	Shear-anterior
93	Shea et al., 1991	iso cerv s	3 adjacent vertebrae,mid	8	5 mm/sec	Shear-anterior
94	Shea et al., 1991	iso cerv s	3 adjacent vertebrae,lower	8	5 mm/sec	Shear-anterior
95	Moroney et al., 1988	iso cerv s	Intact 2 vertebral segments	16	35 segments from 16 cadavers, unembalmed	Shear-anterior
96	Moroney et al., 1988	iso cerv s	Intact 2 vertebral segments	16	35 segments from 16 cadavers, unembalmed	Shear-lateral
97	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, all	16	5 mm/sec	Shear-posterior
98	Shea et al., 1991	iso cerv s	3 adjacent vertebrae,lower	8	5 mm/sec	Shear-posterior
99	Shea et al., 1991	iso cerv s	3 adjacent vertebrae,mid	8	5 mm/sec	Shear-posterior
100	Shea et al, 1991	iso cerv s	3 adjacent vertebrae,lower	8	5 mm/sec	Shear-posterior
101	Moroney et al., 1988	iso cerv s	Intact 2 vertebral segments	16	35 segments from 16 cadavers, unembalmed	Shear-posterior
102	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, all	16	5 mm/sec	Tension
103	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, all	16	5 mm/sec	Tension
104	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, low	8	5 mm/sec	Tension
105	Shea et al., 1991	iso cerv s	3 adjacent vertebrae, mid	8	5 mm/sec	Tension
106	Yamada, 1973	single ver	Single vertebral disk			Tension
107	Yamada, 1973	single ver	Single vertebral disk			Tension
108	Yamada, 1970	iso cerv s	Cervical vertebra			Tension
109	Yamada, 1970	iso cerv s	Cervical disk			Tension
110	Panjabi, 1986	iso cerv s	Single motion segment		25 N	Tension
111	Liu et al., 1982	iso cerv s	Young males			Tension
112	Sances et al., 1982	iso cerv s	Isolated cervical spines(C0 - T3)		quasi-static to 142 cm/sec	Tension
113	Pintar, 1986	iso discs	Isolated intervertbral disks			Tension
114	Pintar, 1986	iso cerv s	Isolated intervertebral disks			Various - 10 different
115	Nusholtz et al., 1986	whole cad	Whole cadaver	10	56kg impactor, varied position of impactor, 4.6 to 5.6 m/sec,1.8-11.1kN loads	

Appendix C

Measurement Description	Measurement	Measurement notes/ Injuries	Comments	
mean peak load	907+519lb			1
vertebra fails	1400lb	Unable to produce dislocation with only hyperflexion, Produced bony fractures prior to ligament tears.		2
disc fails	1600lb	Unable to produce dislocation with only hyperflexion		3
compressive fracture loads	1.47-2.16 kN (330 to 486 lb)			4
Stiffness at 300 N, compress, all	7.18+0.48 e05N/m	low load rate, compression and tension statastically significantly different	Previous experiments showed little difference in stiffness with loading rate.	5
Stiffness at 500 N- compress, all	9.57+2.44 e05 N/m			6
Stiffness at 500 N compress, low	8.0+1.9 e05 N/m			7
Stiffness at 500 N compress,mid	11.14 +2.98 e05 N/m			8
ult compressive strength, compressive breaking load	1.03 kg/mm2, 3089.2 N			9
ult compressive strength, compressive breaking load	1.08 kg/mm2, 3138.2N			10
mean breaking load(kN) in compression,20-39,40-59,60-79	4.09, 3.30, 1.86			11
mean breaking load(kN) in compression,40-59 yo	3.13			12
Measurement range: 1.16-39.24 N/m, axial stiffness	13.18+11.7 N/m		No clear dependence of stiffness on segment location. Compressive stiffness reduced with segment degeneration	13
mean peak crown load, threshold load	1623+301lb, 1281 lb	spinous process fracture, neck went into extension since curvature maintained		14
peak force, impact velocity, impact pulse work value	810 lbs, 20.7 ft/sec, 184 ft-lb	for people with weak or abnormal structures		15
axial stiffness	1.41 e05 N/m			16
axial stiffness	36.9			17
axial stiffness	41.2			18
compression failure load	1030N	C6-C7 segment		19
Failure load in compression	645 N (145 lb)			20
Measured load-deformation for a variety of veloc.	load-deformation curves		Cervical spine load-deformation curves were sensitive to loading rate.	21
			Spinal position relative to load very important in determining fracture type.	22
		C5 Compression fracture	Even 1 cm of eccentricity can influence injury mechanisms.	23

Appendix C

Measurement Description	Measurement	Measurement notes/ Injuries	Comments	
		c4/c5 compression fracture	Even 1 cm of eccentricity can influence injury mechanisms.	24
		C2 cracked	Even 1 cm of eccentricity can influence injury mechanisms.	25
		c1&c2 fracture	Even 1 cm of eccentricity can influence injury mechanisms.	26
		c1 fracture	Even 1 cm of eccentricity can influence injury mechanisms.	27
		c2 fracture	Even 1 cm of eccentricity can influence injury mechanisms.	28
		load relaxation of 70% shown for complete cervical spine after 100+seconds.	Neck's mechanical response can be pre-conditioned.Fracture of pre-conditioned spine significantly depended on positioning	29
varying load rate by a factor of 500		showed a change in stiffness of 1285 to 2250 N/cm for a single specimen		30
mean peak axial load (lb)	1081lb+289lb	compression (burst and wedge fractures), negligible moments reported, 1.4+0.4cm deformation at time of fracture		31
linear cervical-thoracic stiffness	2.2 N-m/deg			32
force to fracture odontoid process: range, mean	1422 to 2540 N, 2059 N	odontoid fracture		33
force to rupture the transverse ligament: range, mean	1334 to 2138, 1775N	rupture of transverse ligament		34
bilateral fracture of neural arches, range	1868 to 1957 N	bilateral fracture of neural arches		35
peak axial load in specimens that had bilateral locked facets	325 lb (6 of 14 specimens)	produced "ducking" shape, bilateral locked facets in 6 of 14		36
mean load, mean deformation (skull and neck)	516+160lb, 2.5+1.0cm	1 compression failure, 2 flexion/compression failures, 4 extension/compression failures		37
mean compression load, deformation	788+437lb, 9-37 mm	lowest wedge fracture force=264 lb, burst=820lb, compression fracture in 4ms, burst fracture in 2ms		38
Bony fracture and anterior longitudinal ligament tears, mean peak crown force	1354+686 lb	four impacts produced no injury,2 basilar skull fracture	Impulse found to be best indicator of injury level (injury level not defined).	39
neck reaction moments about AP, ML, IS (max.level)	125 ft-lb,79 ft-lb,50 ft-lb			40
Strains on anterior surface of C2-C7, left facet joints			Head/neck relative position significantly influences results,crown loading didn't correlate well with cervical strain.	41
peak forces	1.8 to 11.1 kN	cervical fracture produced in all but one case:fracture of spinous process, laminae, transverse process, and vertebral bodies		42

Measurement Description	Measurement	Measurement notes/ Injuries	Comments	
studied neck motions and failure mechanisms			Head/neck relative position significantly influences results, motion of head relative to neck not a good descriptor.	43
		burst c3,c4,c5 - occur in pure compression or compression w/slight flexion	Even 1 cm of eccentricity can influence injury mechanisms.	44
		burst c3,c6 - occur in pure compression or compression w/slight flexion	Even 1 cm of eccentricity can influence injury mechanisms.	45
mean peak axial load (lb)	387lb+277lb	bilateral locked facets, ducking shape- superior in extension, inferior in flexion		46
mean peak axial load, mean peak mom, angle at peak moment	430lb, 6.2 ft-lb, 19deg.	disruption of posterior elements, wedged disc+body		47
measured impact loads	3000 to 14700 N		Injuries to the neck were primarily due to the neck being the major element in stopping the torso.	48
Stiffness at 3.5 Nm-extension, 5Nm flexion,low	1.19+0.43 Nm/deg			49
Stiffness at 3.5 Nm-extension, 5Nm flexion,mid	2.29+1.44 Nm/seg			50
Stiffness at 3.5 Nm-extension, 5Nm flexion,all	1.74+0.93 Nm/deg			51
Stiffness at 5Nm, flexion, extension,all	1.13+0.68 Nm/deg	Flexion and compression were not statistically significantly different		52
extension stiffness	0.73+0.45 Nm/deg			53
peak load	150lb	atlantoaxial dislocation, mean of 3 disloc=231+146		54
		jefferson fracture- occurred in extension-compression	Even 1 cm of eccentricity can influence injury mechanisms.	55
		jefferson fracture- occurred in extension-compression	Even 1 cm of eccentricity can influence injury mechanisms.	56
		extension failure	Even 1 cm of eccentricity can influence injury mechanisms.	57
		jefferson fracture- occurred in extension-compression	Even 1 cm of eccentricity can influence injury mechanisms.	58
		jefferson fracture- occurred in extension-compression	Even 1 cm of eccentricity can influence injury mechanisms.	59
Stiffness at 3.5 Nm-extension, 5Nm flexion,low	0.83 +0.27 Nm/deg			60
Stiffness at 3.5 Nm-extension, 5Nm flexion,mid	1.44+1.08 Nm/deg			61
Stiffness at 3.5 Nm-extension, 5Nm flexion,all	1.13+0.68 Nm/deg			62
Stiffness at 5Nm, flexion, extension,all	1.88+1.18 Nm/deg	Flexion and compression were not statistically significantly different		63
flexion stiffness	0.43+0.23 Nm/deg			64

Appendix C

Measurement Description	Measurement	Measurement notes/ Injuries	Comments	
minimum failure moment, max failure moment in flexion	1.6Nm, 3.4 Nm	C1-C2 segment, C5-C6 segment		65
mean peak load	418+216lb	2 atlantoaxial dislocations		66
dynamic load at flexion-compression failure	400-1000lb (1.78-4.45 kN)			67
		C5 anterior wedge fracture - occurred in flexion-compression	Even 1 cm of eccentricity can influence injury mechanisms.	68
mean peak axial load (lb)	64lb.	no injury, Head allowed to move until chin would have contacted torso.		69
flexion angle change, mean peak axial, moment at inferior end	46deg., 50 lbs., 66in-lb	dislocations with disruption of ligamentum flavum, interspinous and capsular ligaments.		70
right bending stiffness	0.68+0.49 Nm/deg			71
cranial-cervical lateral bending stiffness	3.74N-m/deg			72
cervical-thoracic lateral bending stiffness	2.71 N-m/deg			73
flexion/extension (total), lateral bending (1 side), axial rotation (1 side)	25 deg, 5 deg, 5 deg			74
flexion/extension (total), lateral bending (1 side), axial rotation (1 side)	20 deg, 5 deg, 40 deg			75
Lateral bending range of motion:C0-C1;C1-C2;*mid cervical spine*	8 deg; 0 deg; 10 deg			76
Lateral bending range of motion-whole neck	86 deg			77
Lateral bending range of motion-whole neck	52 deg			78
mean *break load* in torque(Nm),20-39, 40-69	5.5,4.7			79
Counterclockwise torsion stiffness	1.16+0.46 Nm/deg			80
rotational stiffness	0.339 N-m/deg			81
failure torque	13.6Nm	bony fractures of the odontoid process; C0-C1: 3.4 deg; C1-C2 4.2 deg		82
failure torque	14.3Nm	C0-C1 3.4 deg; C1-C2 4.2 deg		83
failure torque	27.9Nm	ligamentous rupture of the alar ligaments; C0-C1: 3.4 deg; C1-C2 4.2 deg	increase in stiffness at higher loading rates	84
failure torque	23.2Nm	C0-C1: 3.4 deg; C1-C2 4.2 deg	400 deg/sec not significantly different than 100 deg/sec	85
Rotational stiffness:0-10 deg., 10-30 deg., greater than 30 deg.	0, 0.25, 0.5 Nm/deg			86
severe neck injuries were produced in 4 of 6		C1-C2 fracture dislocation, ligament tear, ring fractures and cord transections	suggested 1400 lb neck fracture tolerance for this condition.	87

Appendix C

Measurement Description	Measurement	Measurement notes/ Injuries	Comments	
range, mean	117-1765N, 824 N			88
rapid loading (.1 sec), slow loading (1sec)	1088N, 706N			89
force to fracture odontoid process	686.5 to 1765 N			90
Stiffness at 100 N, anterior, posterior shear, all	1.23+0.35 e05 N/m			91
Stiffness at 100N, anterior, posterior shear, low	1.36+0.47 e05 N/m			92
Stiffness at 100 N, anterior, posterior shear,mid	1.10+0.23 e05 N/m			93
Stiffness at150 N, anterior shear, posterior shear	1.83+0.47 e05N/m	Anterior and Posterior shear were not statistically significantly different		94
shear stiffness - anterior	131+157 N/mm			95
right lateral shear stiffness	119+65 N/mm			96
Stiffness at 100 N, anterior, posterior shear, all	1.14+0.69 e05N/m			97
Stiffness at 100N, anterior, posterior shear, low	1.12+1.20 e05N/m			98
Stiffness at 100 N, anterior, posterior shear,mid	1.15+0.18 e05N/m			99
Stiffness at150 N, anterior shear, posterior shear	1.62+0.22 e05N/m	Anterior and Posterior shear were not statistically significantly different		100
shear stiffness-posterior	49+24 N/mm			101
Stiffness at 300 N, tension, all	4.33+0.54 e05N/m	low load rate, compression and tension statistically significantly different		102
Stiffness at 100N- tension,all	1.93+1.24 e05N/m			103
Stiffness at 100 N tension,low	1.57+0.56 e05N/m			104
Stiffness at 100 N tension,mid	2.29 +1.91 e05N/m			105
ult tensile strength, breaking load	0.3 kg/mm2, 863 N			106
ult torsional strength, breaking moment	0.48 kg/mm2, 5.0 N-m			107
mean breaking load (kN) in tension, 20-39yo,40-79y	1.12, 0.89			108
mean breaking load(kN) in tension, 20-39, 40-79	1.03, 0.78			109
tensile stiffness	53kN/m			110
tensile stiffness	590kN/m			111
tensile axial load to failure	1446-1940 N			112
mean tensile stiffness	68kN/m			113
Tensile stiffness of intervertebral disk	68 kN/m			114
Mean peak cervical force when fracture produced	1283.7+714.2	flexion-compression, extension-compression and combined injuries	Head/neck relative position significantly influences results.	115

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MEMORANDUM FOR DTIC-OCQ 2 Jun 00

SUBJECT: Change of Distribution Statement on AL/CF-TR-1995-0038

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1. Please be advised that Technical Report, AL/CF-TR-1995-0038 has been reviewed by the ASC Public Affairs office and has been cleared for public release.

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Patricia M. Lewandowski

PATRICIA M. LEWANDOWSKI
AFRL STINFO Program Manager
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Attachments:
1. AL/CF-TR-1995-0038
2. DTIC Form 50

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