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Retrospective Review of Spinal Injuries in U.S. Army Rotary-wing Mishaps: January 1990–December 2014

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14. ABSTRACT

A retrospective review of spinal injuries in U.S. Army rotary-wing mishaps occurring between 1990 and 2014 was conducted. This report describes the spinal injury trends experienced by seated occupants in mishaps during this study period. Data from U.S. Army Class A and B, rotary-wing, in-flight mishaps between 1990 and 2014 were obtained from the U.S. Army Combat Readiness Center aviation mishap database. Included in the analysis were data from survivable, partially survivable, and non-survivable mishap aircraft that included spinal injuries sustained by seated occupants. A total of 739 Class A and B mishaps occurred involving 765 rotary-wing aircraft and 3117 occupants. Out of 3117 occupants, 1147 were seated when the mishap occurred; 460 of these occupants sustained a total of 547 spinal injuries. Lower thoracic and lumbar vertebrae experienced the largest frequencies of injury. The frequency and location of spinal injuries found in this study were consistent with historical data on spinal injuries sustained in similar mishaps between 1979 and 1985.

15. SUBJECT TERMS
Spinal injury, crashworthy, crashworthy seats, rotary-wing mishap, rotary-wing accident, MIL-S-58095

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Introduction and Military Relevance

The occurrence of spinal injuries during a helicopter mishap can prevent an individual from escaping an aircraft and consequently expose them to increased risk of secondary threats from immediate post-crash factors such as fire, environmental conditions, and enemy action. Such increased risk of secondary injury threats could result not only in further injury to the individual but also death, particularly when in hostile terrain. Spinal injuries can also result in prolonged illness, recovery absence, or even long-term disability, preventing a return to duty as an aviator. These events are potentially life changing for patients as they adapt to reduced mobility, and they may experience limitations in function as a response to frequent or recurring pain.

Spinal injuries affect not only the individual, but are also costly to the Department of Defense; expenses are incurred through treatments, rehabilitation, disability payments, and the costs of training a replacement aviator. The General Accounting Office (1999) (now referred to as the Government Accountability Office) reported that losing pilots and crewmembers reduces unit readiness for combat and is a financial burden as training costs can be more than $9 million per pilot.

The results of this study will provide a review of Army aviation mishap records in rotary-wing aircraft, many with modern safety technology. The data could be used to identify whether current safety technologies have sufficiently mitigated individual risk factors for spinal injuries or created new risk factors. This injury trend information will drive future research in personal protective equipment and aircraft protective equipment for both current and future airframes.

Objective

The purpose of this study was to identify spinal injury trends in seated occupants of Army rotary-wing aircraft involved in Class A and B, rotary-wing, in-flight mishaps over a time period during which crashworthy technologies became more commonplace in fielded aircraft (1990-2014). Trends of spinal injuries, which often result from exposure to high vertical acceleration, can be used to guide future spinal injury prevention research.

Materials and Methods

Data used in this study were obtained from the U.S. Army Combat Readiness Center (USACRC) aviation mishap database. The USACRC is responsible for archiving aviation accident reports for all Army aviation accidents. Each aviation mishap report is also encoded into the aviation mishap database; the database can be analyzed for trends in materiel failures, accident causes, training deficiencies, and occupant injuries. A memorandum of agreement between the USACRC and the U.S. Army Aeromedical Research Laboratory (USAARL), dated 29 August 2016, enables USAARL to access historical accident data for safety and injury trend analysis.

All U.S. Army Class A and B, rotary-wing, in-flight mishaps occurring during a 25-year period (January 1, 1990 through December 31, 2014) were reviewed for this study. Class A mishaps are defined by regulation as accidents resulting in 1) property damage of $2,000,000 or more; 2) the destruction, loss, or abandonment of an Army aircraft; or 3) injury and/or occupational illness that results in a fatality or permanent total disability. Class B mishaps are defined as accidents resulting in 1) a total cost of property damage greater than $500,000 but less than $2,000,000; 2) injury and/or occupational illness resulting in permanent partial disability; or 3) three or more personnel are hospitalized as inpatients as the result of a single occurrence (Department of Defense, 2011). Mishaps classified as C, D, E, and F were not considered in this study since crashes falling under these classifications do not typically involve significant ground contact or injury.

The U.S. Army operated several manned rotary-wing airframes during the 25-year study period. All manned Army rotary-wing airframes considered during this retrospective review are presented in Table 1. The USACRC database contained mishap information for variants of each Army rotary-wing airframe. For this study, aircraft were categorized by basic airframe model (e.g., AH-64, UH-60, CH-47, etc.). The basic airframe categories and individual variants included in each are shown in Table 1.

Each aircraft involved in a U.S. Army aviation mishap receives a classification: survivable (S), partially-survivable (PS), and non-survivable (NS) based on two factors: aircraft kinematics and preservation of occupiable space per DA PAM 385-40 (Department of the Army [DA], 2015). For instance, if multiple aircraft are involved in a mishap, each mishap aircraft receives its unique survivability classification. A mishap aircraft receives a survivable classification if the aircraft impact accelerations remained within human tolerance and the occupiable space around the occupants was not compromised for all seat/litter positions. A mishap aircraft receives a partially-survivable classification if impact accelerations remain within human tolerance and occupiable space is maintained for at least one seat/litter position. If no seat/litter positions meet these two criteria, the mishap aircraft receives a non-survivable classification (DA, 2015). All mishap aircraft survivability classifications were included in this analysis. Mishap cases were not down-selected or filtered out according to mishap aircraft survivability classification.

This study was intended to investigate spinal injury trends in seated occupants of Army rotary-wing mishaps meeting the study inclusion criteria (i.e., Class A and B, in-flight, rotary-wing mishaps occurring between January 1, 1990, and December 31, 2014). The occupancy and seating status of each individual injured as a result of these mishaps were reviewed to eliminate individuals that were not occupants of an aircraft or were not seated in an aircraft during the mishap. Non-occupants included injured Service Members or civilians on the ground in the vicinity of the mishap at the time it occurred, as well as individuals who were coded as being "thrown from" the aircraft during the mishap. The latter group was excluded from the analysis as it was unknown if their injuries resulted from the initial aircraft ground contact while a seated occupant or from the individual being thrown from the aircraft.

Individuals considered to be an occupant of a mishap aircraft were further filtered to eliminate those not seated during the mishap event. The USACRC aviation mishap database included data on an occupant's seat use; individuals were coded as being "in seat," "not in seat," “undetermined,” or the field was blank. Aircraft occupants were assumed to be seated unless coded as being “not in seat” in the mishap database.

All injuries to seated occupants involved in mishaps meeting the study inclusion criteria were obtained from the USACRC aviation mishap database. For this review, injuries to body regions other than the pelvis and spine were excluded from this analysis. Spinal and pelvic injuries included any injury to the body regions listed in Table 2. Injuries to the basilar skull were included as the base of the skull is considered to the uppermost portion of the cervical spine. The pelvis serves as the interface between the aircraft seat and the spine; during a vertical impact, accelerations are transmitted from the aircraft to the seat and from the seat through the pelvis and into the spinal column. For this reason, pelvis injuries were included in this analysis to evaluate potential relationships between pelvic and spinal injuries.

Spinal injuries were grouped into minor and major injury severity categories. Abbreviated Injury Scale codes were not available for all spinal injuries. As a result, the research team collectively determined spinal injury severity based on the type of injury and spinal region affected (Table 3).

The frequency (counts) of minor and major spinal injuries were determined for each level of the spine and pelvis shown in Table 2 for the four mishap aircraft survivability classifications: survivable, partially-survivable, non-survivable, and not reported/not applicable. Injury counts were used to compute the total number of injuries in the spine or pelvis, as well as the proportion of total spinal or pelvis injuries associated with specific injury severities (minor or major), anatomic regions, and mishap aircraft survivability classifications. Injury frequencies (counts) were used to investigate the occurrence of co-morbid spinal and pelvic injuries; injury counts were used to compute the proportion of occupants who sustained pelvic or spinal injuries at one vertebral level co-morbidly with spinal injuries at other vertebral levels.

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Table 1. U.S. Army Rotary-wing aircraft included in present study

Basic airframe	AH-1	UH-1	OH-6	CH-47	OH-58	UH-60	AH-64	TH-67	UH-72
Airframe variants	AH-1E AH-1F AH-1S	UH-1H UH-1M UH-1V JUH-1H	AH-6J AH-6M MH-6C MH-6J MH-6M OH-6A EMH-6J	CH-47D CH-47F MH-47D MH-47E MH-47G	OH-58A OH-58C OH-58D OH-58DI OH-58DR	EH-60A HH-60L HH-60M MH-60A MH-60K MH-60L MH-60M UH-60A UH-60L UH-60M	AH-64A AH-64D AH-64E	TH-67A	UH-72A
Name	Cobra	Iroquois	Little Bird	Chinook	Kiowa	Blackhawk	Apache	Creek	Lakota
Mission	Attack	Utility/ MEDEVAC*	Scout/ Attack	Medium lift	Scout/ Attack	Utility/ MEDEVAC*	Attack	Training	Training/ MEDEVAC*
Seating capacity	2	14	2-4	4-35	2-4	16	2	4	8

* Medical evacuation (MEDEVAC)

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Table 2. USACRC database body part descriptions related to injuries of interest

Multiple Bones (Basilar)	Vertebra T6	Intervertebral Disk
Atlanto-occipital	Vertebra T7	Spinal Cord, General
Vertebra C1	Vertebra T8	Vertebra
Vertebra C2	Vertebra T9	Vertebrate
Vertebra C3	Vertebra T10	Vertebra, General
Vertebra C4	Vertebra T11	Vertebra, Lumbar
Vertebra C5	Vertebra T12	Vertebra, Multi-Thoracic
Vertebra C6	Vertebra L1	Neck, General
Vertebra C7	Vertebra L2	Neck, Not Further Specified
Vertebra T1	Vertebra L3	Back, General
Vertebra T2	Vertebra L4	Back, Not Further Specified
Vertebra T3	Vertebra L5	Peri-lumbar Muscles
Vertebra T4	Sacrum	Pelvis, General
Vertebra T5	Coccyx	Pelvis, Not Further Specified

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Table 3. USACRC database injury type descriptions for major and minor spinal injury categories

Injury type description	Injury severity
Chip	Minor injury
Strain (Stretched Ligaments Or Muscles)	Minor injury
Stress Injuries, NFS	Minor injury
Contusion (Bruise, Hematoma)	Minor injury unless associated with (UAW) spinal cord
Laceration/Cut	Minor injury UAW spinal cord
Avulsion (Evisceration)	Major injury
Blowout	Major injury
Compression	Major injury
Crushed/Depressed	Major injury
Dislocation	Major injury
Fracture, NFS	Major injury
Herniation / Rupture	Major injury
Injury, NFS	Major injury
Paralyzed	Major injury
Transection (Cut Across)	Major injury
Unknown	Major injury
Wounds, NFS	Major injury
Comminuted	Major injury UAW Sacrum
Fracture – Dislocation	Major injury UAW Coccyx
Fractures (UNQ)	Major injury UAW Coccyx
Linear	Major injury UAW Sacrum
Simple (Closed)	Major injury UAW Sacrum or Coccyx
Sprain (Wrenching Joint Stretch/Tear Ligaments)	Major injury UAW Sacrum or Back (general)
Transverse	Major injury UAW Coccyx

This study was conducted under a human subjects research protocol approved by the U.S. Army Medical Research and Development Command (USAMRDC) Office of Research Protections in accordance with 32CFR219 (Protection of Human Subjects, 2013) and met all requirements for waiver of the need to obtain informed consent from the individuals whose injury data were included in this study. USACRC database records were anonymized before viewing by the research team; individuals involved in the aviation mishaps of interest were identified by a unique combination of the mishap case number and personnel number assigned by the USACRC.

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Results

General

A total of 739 U.S. Army Class A and B, rotary-wing, in-flight mishaps occurred during the 25-year study period of January 1, 1990 through December 31, 2014. These mishaps involved 765 rotary-wing aircraft and 3117 occupants (Table 4). Fifty-five percent of the occupants involved in these 739 mishaps were uninjured (1708 of 3117), while 45% (1406 of 3117) suffered fatal, disabling, or non-disabling injuries (Table 4). The majority of the mishap aircraft were classified as survivable (63%) or partially survivable (9%). The survivability of 134 of 765 mishap aircraft (18%) was codified as not reported or not applicable, as shown in Table 5.

Table 4. Summary of U.S. Army class A and B rotary-wing mishaps: January 1990 through December 2014

	Total mishaps 739*		
	Class A 478		
	Class B 287		
Total aircraft	765*	Total aircraft occupants	3117
AH-1	22	Fatalities	445
UH-1	56	Disabling injury	635
OH-6	24	Non-disabling injury	326
CH-47	76	Missing occupants	3
OH-58	182	No injury	1708
UH-60	209		
AH-64	174		
TH-67	19		
UH-72	3		

*The total number of aircraft (765) exceeds the total number of mishaps (739) due to some mishaps involving more than one aircraft.

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Table 5. Survivability classifications for aircraft involved in the 739 mishaps meeting study inclusion criteria

	Survivable	Partially survivable	Non-survivable	Not reported/ Not applicable	Total
AH-1	18 (82)	1 (5)	3 (14)	0 (0)	22
UH-1	37 (66)	3 (5)	13 (23)	3 (5)	56
OH-6	17 (71)	1 (4)	2 (8)	4 (17)	24
CH-47	46 (61)	6 (8)	7 (9)	17 (22)	76
OH-58	122 (67)	11 (6)	29 (16)	20 (11)	182
UH-60	117 (56)	24 (12)	18 (8)	50 (24)	209
AH-64	108 (62)	19 (11)	13 (7)	34 (20)	174
TH-67	13 (68)	2 (11)	0 (0)	4 (21)	19
UH-72	1 (33)	0 (0)	0 (0)	2 (67)	3
Totals	479 (63)	67 (9)	85 (11)	134 (18)	765

( ) indicates row percent rounded to the nearest whole number

Of the 1406 injured (including deceased) occupants, 27 occupants were coded as being thrown from the aircraft during the mishap sequence. As mentioned previously, these individuals and their injuries were excluded from analysis, i.e., considered non-occupants, as it was unknown whether their injuries were a result of initial aircraft ground contact while a seated occupant or from the occupant being thrown from the aircraft. The USACRC aviation mishap database did not contain injury data for 217 injured (including deceased) aircraft occupants. Injury data were available in the USACRC aviation mishap data for the remaining 1162 aircraft occupants.

Spinal Injuries

Of the 1162 aircraft occupants with injuries for which injury data was available, 1147 injured occupants (98.7%) were identified as being seated at the time of the mishap. Within the 1147 seated injured occupants, 460 occupants (40.1%) sustained spinal injuries; the remaining 687 occupants sustained no spinal injuries. Fifteen (15) of 1162 injured aircraft occupants (1.3%) were identified as not being seated at the time of the mishap; of these, 12 occupants (80%) sustained spinal injuries.

The 460 seated injured occupants sustained 547 spinal injuries. Table 6 shows the frequency of all spinal injuries by airframe type and mishap aircraft survivability classification. Overall, 72.7% of spinal injuries (398 of 547) occurred in survivable and partially-survivable mishap aircraft.

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Table 6. Spinal injury frequency by basic airframe and survivability classification

	Survivable	Partially-survivable	Non-survivable	Not reported/ Not applicable	Total
AH-1	8 (100)	0 (0)	0 (0)	0 (0)	8
UH-1	34 (59)	3 (5)	21 (36)	0 (0)	58
OH-6	17 (71)	0 (0)	4 (17)	3 (13)	24
CH-47	28 (41)	16 (24)	11 (16)	13 (19)	68
OH-58	60 (54)	13 (12)	37 (33)	1 (1)	111
UH-60	90 (50)	48 (27)	34 (19)	9 (5)	181
AH-64	41 (51)	26 (32)	13 (16)	1 (1)	81
TH-67	6 (46)	7 (54)	0 (0)	0 (0)	13
UH-72	1 (33)	0 (0)	0 (0)	2 (67)	3
Totals	285 (52)	113 (21)	120 (22)	29 (5)	547

( ) indicates row percent rounded to the nearest whole number; injury frequencies include major and minor spinal injuries.

Total spinal injuries were separated into minor and major injuries in Tables 7 and 8, respectively; these tables show the frequency of minor and major spinal injuries by vertebral level and mishap aircraft survivability classification. Minor spinal injuries accounted for 44.2% (242 of 547) of all spinal injuries (Table 7). The majority of minor spinal injuries (227 of 242, 93.8%) were sustained by occupants of survivable and partially survivable mishap aircraft; these 227 minor spinal injuries represented 41.5% of total spinal injuries sustained during the study period (Table 7). Major spinal injuries accounted for 55.8% (305 of 547) of all spinal injuries. More than half of the major spinal injuries were sustained by the combined occupants of survivable and partially-survivable mishap aircraft (56.1%, 171 of 305), while 38.7% of the major spinal injuries occurred in occupants of non-survivable mishap aircraft (118 of 305) (Table 8).

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Table 7. Frequency of minor spinal injuries by vertebral level and mishap aircraft survivability classification

	Survivable	Partially Survivable	Non-Survivable	Not Reported/ Not Applicable	Total
Multiple Bones (Basilar)	0	0	0	0	0
Atlanto-occipital	0	0	0	0	0
Vertebra C1	0	0	0	0	0
Vertebra C2	0	0	0	0	0
Vertebra C3	0	0	0	0	0
Vertebra C4	0	0	0	0	0
Vertebra C5	1	0	0	0	1
Vertebra C6	1	0	0	0	1
Vertebra C7	0	0	0	0	0
Vertebra T1	0	0	0	0	0
Vertebra T2	0	0	0	0	0
Vertebra T3	0	0	0	0	0
Vertebra T4	0	0	0	0	0
Vertebra T5	0	0	0	0	0
Vertebra T6	1	0	0	0	1
Vertebra T7	0	0	0	0	0
Vertebra T8	0	0	0	0	0
Vertebra T9	0	0	0	0	0
Vertebra T10	0	0	0	0	0
Vertebra T11	0	1	0	0	1
Vertebra T12	0	0	0	0	0
Vertebra L1	1	0	0	0	1
Vertebra L2	1	0	0	0	1
Vertebra L3	0	0	0	0	0
Vertebra L4	0	0	0	0	0
Vertebra L5	4	0	0	0	4
Sacrum	8	2	0	0	10
Coccyx	8	1	0	1	10
Intervertebral Disk	1	1	0	0	2
Spinal Cord, General	0	0	0	0	0
Vertebra	1	0	0	0	1
Vertebrate	0	0	0	0	0
Vertebra, General	4	2	0	0	6
Vertebra, Lumbar	16	2	0	0	18
Vertebra, Multi-Thoracic	4	0	0	0	4
Neck, General	52	4	0	0	56
Neck, NFS*	9	1	0	0	10
Back, General	64	14	1	12	91
Back, NFS*	21	1	1	0	23
Peri-lumbar Muscles	1	0	0	0	1
Total	198	29	2	13	242

* NFS = Not further specified

Table 8. Frequency of major spinal injuries by vertebral level and mishap aircraft survivability classification

	Survivable	Partially Survivable	Non-Survivable	Not Reported/ Not Applicable	Total
Multiple Bones (Basilar)	2	4	9	0	15
Atlanto-occipital	0	1	9	1	11
Vertebra C1	0	2	9	0	11
Vertebra C2	0	4	5	0	9
Vertebra C3	1	1	4	1	7
Vertebra C4	1	1	0	0	2
Vertebra C5	0	1	2	0	3
Vertebra C6	2	2	5	1	10
Vertebra C7	4	1	2	0	7
Vertebra T1	0	0	4	0	4
Vertebra T2	0	2	0	0	2
Vertebra T3	0	2	3	0	5
Vertebra T4	4	0	3	0	7
Vertebra T5	0	0	1	1	2
Vertebra T6	1	0	1	0	2
Vertebra T7	2	1	3	1	7
Vertebra T8	2	0	1	0	3
Vertebra T9	0	0	0	0	0
Vertebra T10	1	3	1	0	5
Vertebra T11	1	3	3	0	7
Vertebra T12	7	5	2	3	17
Vertebra L1	21	9	1	1	32
Vertebra L2	14	6	1	0	21
Vertebra L3	3	3	1	0	7
Vertebra L4	5	4	2	0	11
Vertebra L5	1	0	0	0	1
Sacrum	0	0	0	0	0
Coccyx	0	0	0	0	0
Intervertebral Disk	0	1	0	0	1
Spinal Cord, General	3	6	9	2	20
Vertebra	2	5	7	1	15
Vertebrate	0	1	1	0	2
Vertebra, General	2	1	8	2	13
Vertebra, Lumbar	6	9	12	0	27
Vertebra, Multi-Thoracic	2	4	2	2	10
Neck, General	0	2	4	0	6
Neck, NFS*	0	0	3	0	3
Back, General	0	0	0	0	0
Back, NFS*	0	0	0	0	0
Peri-lumbar Muscles	0	0	0	0	0
Total	87	84	118	16	305

* NFS = Not further specified

Figures 1 and 2 illustrate the proportion total spinal injuries attributed to minor and major spinal injuries, respectively, by vertebral level and two mishap aircraft survivability groups: survivable and partially-survivable mishap aircraft combined (S+PS) and non-survivable (NS) mishap aircraft. Minor spinal injuries were generally associated with general anatomic regions such as “Neck, General” or “Back, General” rather than specific vertebral levels within the spine (Figure 1). For almost all levels of the cervical spine, the proportion of total spinal injuries associated with non-survivable mishap aircraft were higher than those associated with the combined group of survivable and partially-survivable mishap aircraft (Figure 2).

Figure 2 also shows that the thoracolumbar spine (T11-L5) appears to be a region of the spine most at risk for injury in survivable and partially-survivable mishap aircraft. For occupants in these mishap aircraft, the proportion of total spinal injuries associated with vertebral levels T11 to L5 is higher than the proportions of total spinal injuries associated with vertebral levels superior to T11 (Figure 2). Specifically, Table 8 shows that major injuries to T11 through L5 represent 97 of 547 total spinal injuries (17.7%); the 97 injuries include those associated with the general anatomic region of “Vertebra, Lumbar”. The upper two-thirds of the column [Multiple Bones (Basilar) to T10] sustained 51 major spinal injuries in survivable and partially-survivable mishap aircraft; the 51 major injuries, which include major injuries associated with the general anatomic region “Vertebra, Multi-Thoracic” represent 9.3% of all spinal injuries. For occupants of survivable and partially-survivable mishap aircraft, the lower one-third of the spine (T11 to L5) sustained 1.9 times the major injuries as the upper two-thirds of the spine (97/51 = 1.9, Table 8).

Within the thoracolumbar portion of the spine, L1 appears to be the most at risk of injury (Figure 2). The L1 vertebra sustained nearly 30 of 547 total spinal injuries sustained during the study period in survivable and partially-survivable mishap aircraft (5.5%). The next most injured portion of the thoracolumbar spine was L2, which sustained 20 of 547 total spinal injuries (3.7%). Within the thoracolumbar spine, L1 was at least 1.5 times more likely to sustain a major injury than any other thoracolumbar vertebra (T11 to L5).

Previous research has also shown the thoracolumbar spine, particularly L1, to be at the greatest risk of injury in survivable and partially-survivable aircraft involved in rotary-wing mishaps. Shanahan and Shanahan (1989) reported injuries from survivable, partially survivable, and non-survivable, Class A and B, Army rotary-wing mishaps occurring during a 6-year period (October 1, 1979 through September 30, 1985). Eighty-three (83) spinal fractures were sustained by occupants of survivable and partially-survivable aircraft involved in rotary-wing mishaps during the 6-year study period (Shanahan & Shanahan, 1989) (Table 9). Of the 83 spinal fractures, 57 fractures occurred between T11 and L5, which accounts for 68.7% of the total spinal fractures reported by Shanahan and Shanahan (1989) (Table 9). The vertebral level with the highest proportion of fractures was L1 (22 of 83, or 26.5%) (Table 9 and Figure 3).

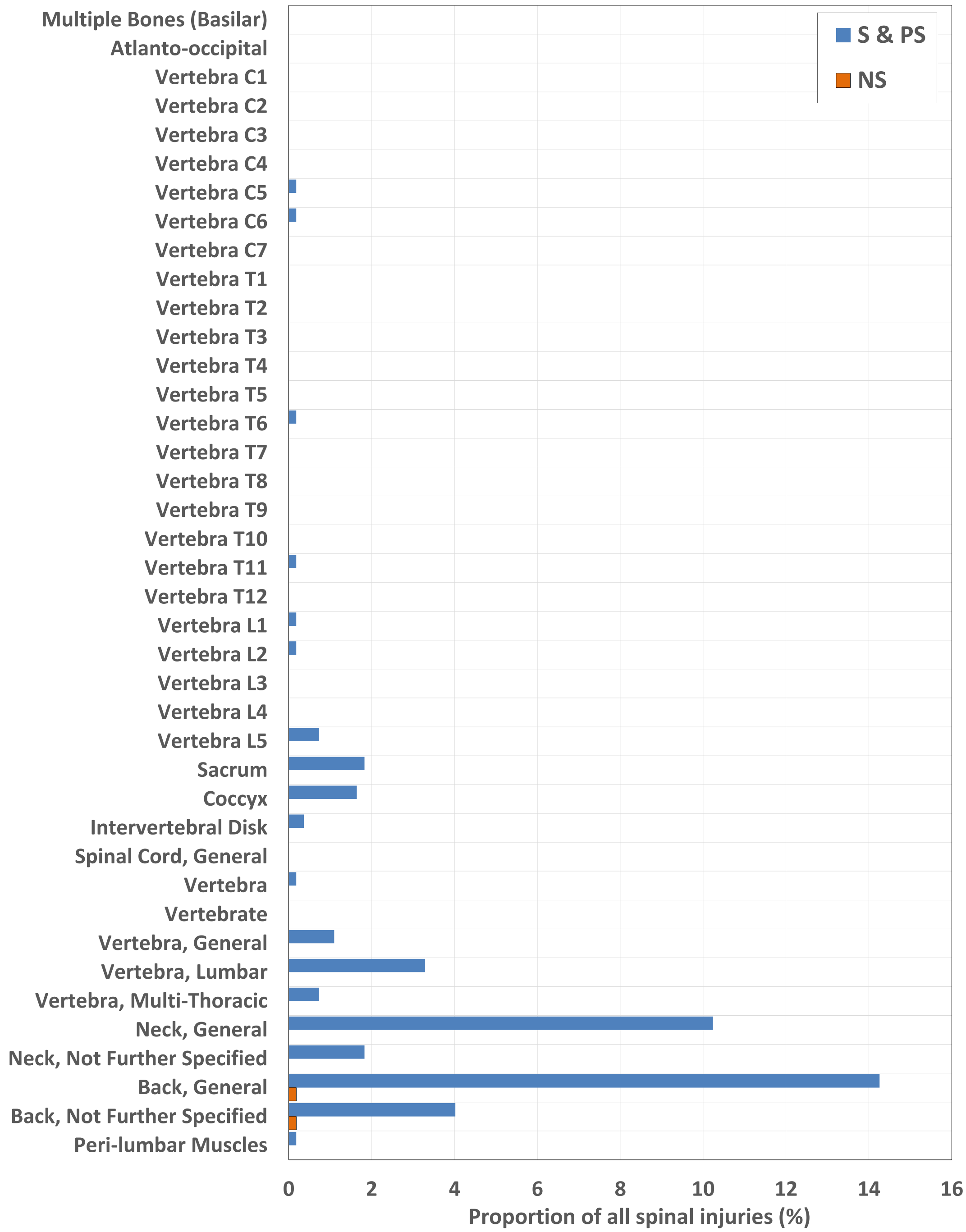

Figure 1. Distribution of minor spinal injuries (expressed as a proportion of all spinal injuries) by vertebral level for two mishap aircraft survivability groups: survivable and partially-survivable classifications combined (S+PS) and the non-survivable (NS) classification. Injury data are presented in anatomical order from top to bottom, starting with the basilar skull and moving down the spine to the coccyx; additional, non-specific spine-related anatomical regions are listed after the coccyx.

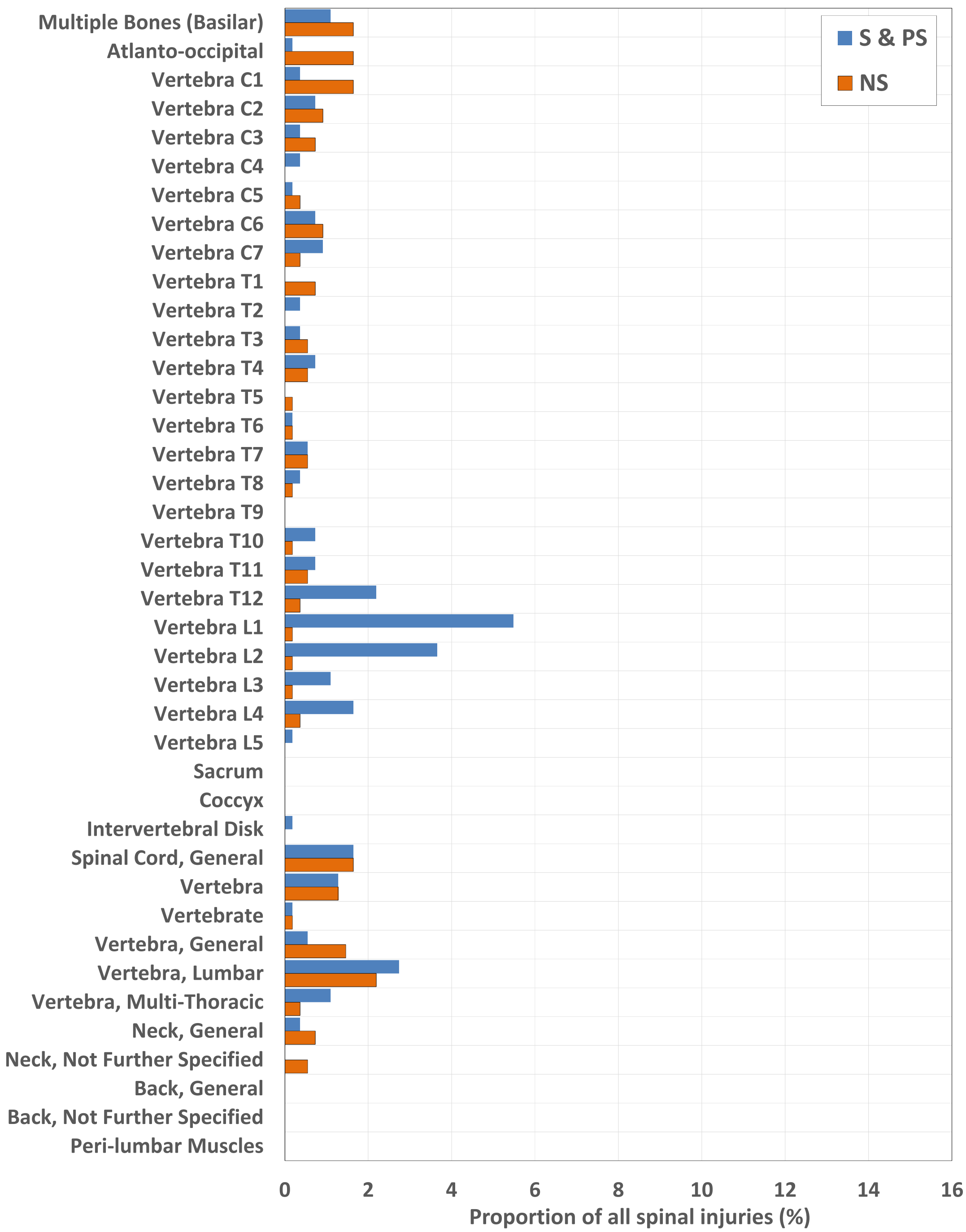

Figure 2. Distribution of major spinal injuries (expressed as a proportion of all spinal injuries) by vertebral level for two mishap aircraft survivability groups: survivable and partially-survivable classifications combined (S+PS) and the non-survivable (NS) classification. Injury data are presented in anatomical order from top to bottom, starting with the basilar skull and moving down the spine to the coccyx; additional, non-specific spine-related anatomical regions are listed after the coccyx.

Table 9. Frequency of spinal fractures sustained by occupants of survivable and partially survivable mishap aircraft by vertebral level as reported by Shanahan and Shanahan (1989)

Vertebra C1	1
Vertebra C2	1
Vertebra C3	1
Vertebra C4	0
Vertebra C5	0
Vertebra C6	1
Vertebra C7	6
Vertebra T1	0
Vertebra T2	1
Vertebra T3	0
Vertebra T4	2
Vertebra T5	2
Vertebra T6	5
Vertebra T7	1
Vertebra T8	1
Vertebra T9	3
Vertebra T10	1
Vertebra T11	4
Vertebra T12	8
Vertebra L1	22
Vertebra L2	11
Vertebra L3	6
Vertebra L4	4
Vertebra L5	2
Total	83

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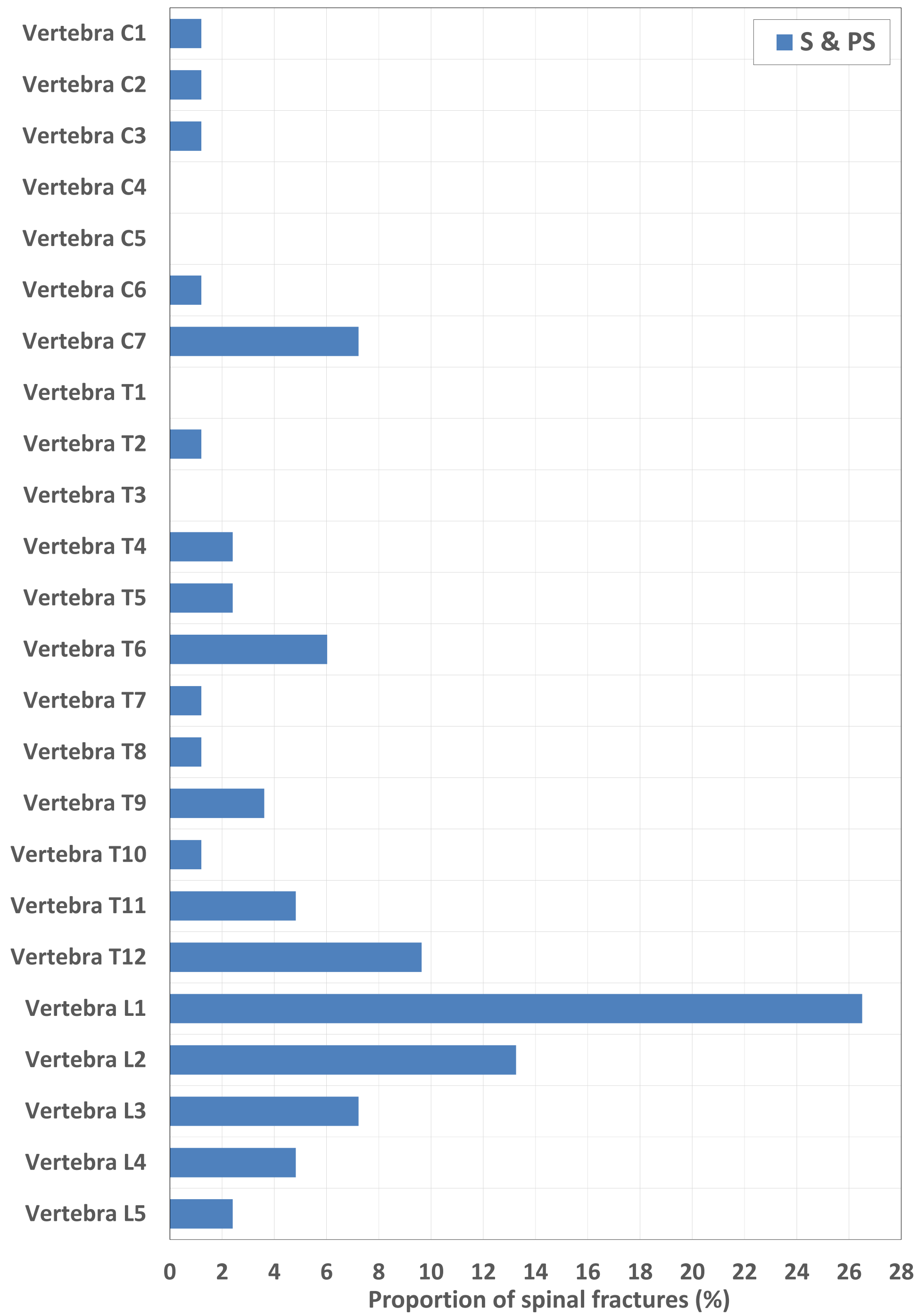

Figure 3. Spinal fracture frequency (expressed as a proportion of total spinal fractures) by vertebral level for survivable and partially-survivable mishap aircraft from Shanahan and Shanahan (1989).

Pelvic Injuries

Pelvic injuries were categorized in the USACRC aviation mishap database by two body regions: “Pelvis, General” and “Pelvis, Not Further Specified” (Table 2). These body regions are anatomically vague and considering them separately would not provide insights about the risk of injury to specific portions of the pelvis (e.g., acetabulum, pelvic ring, etc.). Therefore, for this report, pelvic injuries were aggregated.

Pelvic injury frequency is presented by airframe type for all aircraft survivability classifications (Table 10). Pelvic injuries occurred more often in non-survivable mishap aircraft than in survivable and partially-survivable mishap aircraft combined. More than half of the pelvis injuries were sustained by the occupants of non-survivable mishap aircraft (57.8%, 48 of 83) (Table 10), while 37.3% of the pelvic injuries were sustained by occupants of survivable and partially-survivable mishap aircraft (Table 10).

Table 10. Pelvic injury frequency by basic airframe and survivability classification

	Survivable	Partially-survivable	Non-survivable	Not reported/ Not applicable	Total
AH-1	0 (0)	0 (0)	2 (100)	0 (0)	2
UH-1	1 (10)	0 (0)	9 (90)	0 (0)	10
OH-6	0 (0)	0 (0)	2 (100)	0 (0)	2
CH-47	0 (0)	7 (41)	9 (53)	1 (6)	17
OH-58	5 (24)	3 (14)	13 (62)	0 (0)	21
UH-60	1 (4)	12 (52)	8 (35)	2 (9)	23
AH-64	1 (14)	1 (14)	5 (72)	0 (0)	7
TH-67	0	0	0	0	0
UH-72	0 (0)	0 (0)	0 (0)	1 (100)	1
Totals	8 (10)	23 (28)	48 (58)	4 (5)	83

( ) indicates row percent rounded to the nearest whole number

Co-morbid Injury Relationships

Injury data were analyzed to investigate the occurrence of co-morbid spinal and pelvic injuries; in this analysis, the number of occupants sustaining injuries at multiple vertebral levels, or co-morbid spinal and pelvic injuries were identified. These data are presented in Tables 11 and 12 as the proportions of occupants of survivable and partially-survivable mishap aircraft combined and non-survivable mishap aircraft, respectively, who sustained pelvic or spinal injuries at one vertebral level co-morbidly with spinal injuries at other vertebral levels. For example, Table 11 shows that 17% of the 30 occupants sustaining an L1 spinal injury in survivable and partially-survivable mishap aircraft also sustained an L2 spinal injury; conversely, 25% of the 20 occupants with an L2 spinal injury also sustained an injury to L1 (Table 11).

Table 11. Proportion of individuals sustaining co-morbid spinal and pelvic injuries for survivable and partially-survivable mishap aircraft. Shaded cells represent non-zero entries. Proportions could not be calculated for T1, T5, and T9, as no spinal injuries were reported for these vertebral levels.

		Basilar	A-O	C1	C2	C3	C4	C5	C6	C7	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	L1	L2	L3	L4	L5	Sacrum	Coccyx	Pelvis
Basilar	n = 6	--	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33
A-O	n = 1	0	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
C1	n = 2	50	0	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50
C2	n = 4	0	0	0	--	25	0	0	0	25	0	25	50	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0
C3	n = 2	0	0	0	50	--	50	0	0	50	0	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C4	n = 2	0	0	0	0	50	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C5	n = 2	0	0	0	0	0	0	--	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C6	n = 5	0	0	0	0	0	0	20	--	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0
C7	n = 5	0	0	0	20	20	0	0	0	--	0	20	20	20	0	20	0	0	0	0	0	0	20	20	20	20	0	0	0	0
T1	n = 0										--																			
T2	n = 2	0	0	0	50	50	0	0	0	50	0	--	50	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0
T3	n = 2	0	0	0	100	50	0	0	0	50	0	50	--	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0
T4	n = 4	0	0	0	0	0	0	0	0	25	0	0	0	--	0	25	0	0	0	0	0	0	50	50	0	0	0	0	0	0
T5	n = 0														--															
T6	n = 2	0	0	0	0	0	0	0	0	50	0	0	0	50	0	--	0	0	0	0	0	0	50	50	0	0	0	0	0	0
T7	n = 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	33	0	0	0	0	0	0	0	0	0	0	0	0
T8	n = 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	--	0	0	0	0	0	0	0	0	0	0	0	0
T9	n = 0																		--											
T10	n = 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	25	0	0	0	0	0	0	0	0	0
T11	n = 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	--	60	0	0	0	0	0	0	0	0
T12	n = 11	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	27	--	18	0	0	0	0	0	9	0
L1	n = 30	0	0	0	3	0	0	0	0	3	0	0	3	7	0	3	0	0	0	0	0	7	--	17	3	0	0	0	3	3
L2	n = 20	0	0	0	0	0	0	0	0	5	0	0	0	10	0	5	0	0	0	0	0	0	25	--	10	0	0	0	0	5
L3	n = 6	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	17	33	--	17	0	0	0	0
L4	n = 8	0	0	0	0	0	0	0	0	13	0	13	0	0	0	0	0	0	0	0	0	0	0	0	13	--	13	0	0	0
L5	n = 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	--	0	0	0
Sacrum	n = 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	10	0
Coccyx	n = 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	11	0	0	0	0	11	--	0
Pelvis	n = 30	7	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	--

Table 12. Proportion of individuals sustaining co-morbid spinal and pelvic injuries for non-survivable mishap aircraft. Shaded cells represent non-zero entries. Proportions could not be calculated for C4, T2, T9, L5, Sacrum, and Coccyx, as no spinal injuries were reported for these vertebral levels.

		Basilar	A-O	C1	C2	C3	C4	C5	C6	C7	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	L1	L2	L3	L4	L5	Sacrum	Coccyx	Pelvis
Basilar	n = 9	--	11	22	22	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22
A-O	n = 9	11	--	0	0	11	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22
C1	n = 9	22	0	--	22	11	0	0	0	0	0	0	11	0	0	0	0	11	0	0	11	0	0	0	0	0	0	0	0	22
C2	n = 5	40	0	40	--	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	n = 4	0	25	25	25	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C4	n = 0						--																							
C5	n = 2	0	0	0	0	0	0	--	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C6	n = 5	0	0	0	0	0	0	20	--	20	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C7	n = 2	0	0	0	0	0	0	0	50	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1	n = 4	25	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50
T2	n = 0											--																		
T3	n = 3	0	0	33	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33
T4	n = 3	0	33	0	0	0	0	0	33	0	0	0	0	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T5	n = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T6	n = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T7	n = 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	0	0	0	0	0
T8	n = 1	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	0	0	0	0
T9	n = 0																		--											
T10	n = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	0	0
T11	n = 3	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	0
T12	n = 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0
L1	n = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0	0
L2	n = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	0	0	0	0	0	0
L3	n = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--	100	0	0	0	0
L4	n = 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	--	0	0	0	0
L5	n = 0																										--			
Sacrum	n = 0																											--		
Coccyx	n = 0																												--	
Pelvis	n = 44	5	5	5	0	0	0	0	0	0	5	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	--

This analysis was limited to the pelvis and discrete vertebral levels; data for general anatomic regions (e.g., “Back, General”) were not included in this analysis. It should be noted that for many vertebral levels, the number of occupants sustaining an injury is small; this can cause the related proportions to appear artificially inflated. Of primary interest in this analysis was identifying the occurrence of co-morbid injuries.

Spinal injuries were not shown to occur in isolation. Patterns of co-morbid injuries can be seen in Tables 11 and 12, particularly along the upper left to lower right diagonal of the tables. For visual reference, the cells along this diagonal contain non-numeric characters “--.” For survivable and partially-survivable mishap aircraft combined, spinal injuries occurred co-morbidly with one another. Injuries to the upper two-thirds of the spine (basilar to T10) are shown to have occurred in conjunction with injuries to either a superior or inferior vertebral level (Table 11). As an example, 20% of occupants with a C6 injury also had an injury to C5 (Table 11). For the lower one-third of the spine (T11 to L5), spinal injuries are shown to have occurred co-morbidly with injuries to superior and inferior vertebral levels. For occupants with an injury to L2 (n = 20), 25% of these occupants also sustained injuries to L1 and 10% sustained injuries to L3 (Table 11).

Similar trends of co-morbid spinal injuries were shown for occupants of non-survivable aircraft. Table 12 shows that occupants of non-survivable mishap aircraft sustained injuries primarily in the cervical spine and that some occupants sustained injuries at multiple cervical spine levels. As an example, occupants sustaining basilar skull injuries also sustained injuries to the A-O joint, C1, and C2, and occupants sustaining injuries to C2 also sustained injuries to the basilar skull, C1, and C3 (Table 12). Unlike the occupants of survivable and partially-survivable mishap aircraft, occupants of non-survivable mishap aircraft did not sustain co-morbid thoracic or lumbar spine injuries.

For both aircraft survivability groups, pelvic injuries did not commonly occur in conjunction with spinal injuries (Tables 11 and 12). Table 11 shows that less than 10% of 30 occupants sustaining pelvic injuries also sustained injuries to the cervical or lumbar spine. Similarly, Table 12 shows that less than 10% of 44 occupants sustaining pelvic injuries also sustained injuries to the cervical or thoracic spine.

Discussion

The results of this study suggest that being seated in an aircraft seat reduces the potential for spinal injuries. Seated occupants had a lower incidence of sustaining spinal injury (40.1%, 460 of 1147) than non-seated occupants (80%, 12 of 15). Seated occupants are often restrained during the accident sequence, while non-seated occupants are likely unrestrained and free to flail within the aircraft structure, increasing the potential for injury. Additionally, many aircraft are equipped with energy-absorbing seats, which are designed to limit spinal loads during an aircraft mishap; occupants of energy-absorbing seats are provided with additional protection against spinal fractures. While the results of this study suggest that seated occupants sustained a lower incidence of spinal injuries, the two populations (seated versus non-seated) cannot be statistically compared due to the difference in the size of the two populations (1147 versus 15).

The locations of spinal injuries remained consistent between the late 1980s and the current study period (1990-2014). The frequency of spinal injuries was compared between the current study and a previous retrospective study of rotary-wing injuries (Shanahan & Shanahan, 1989). Both studies showed that the lower one-third of the spine (T11 to L5) had a higher combined spinal injury frequency than the upper two-thirds of the spine [Multiple Bones (Basilar) to T10] (Tables 7, 8, and 9). These same tables show that the first lumbar vertebra (L1) was the most frequently injured vertebral body in both studies. These results indicate that the lower one-third of the spine is the most vulnerable portion of the spine during a dynamic mishap event, which is not an unexpected finding since this portion of the spine supports a large portion of an occupant's torso mass. During a dynamic event, the inertial loads on the lower third of the spine increase as a function of the acceleration experienced by the occupant, causing the lower third of the spine to potentially support a higher compressive load. These compressive loads are often sufficient to result in multiple vertebral body fractures as indicated by the incidence of co-morbid fractures of multiple adjacent vertebral levels within the lower third of the spine (Table 11).

Pelvic and spinal injuries did not often occur co-morbidly. In survivable and partially-survivable mishap aircraft (Table 11), the number of occupants sustaining an injury to the L1 vertebra was the same as the number of occupants sustaining pelvic injuries (n = 30). However, the groups of occupants sustaining these two injuries were different as indicated by as indicated by only 3% of occupants sustaining an L1 injury who also sustained a pelvic injury (Table 11). Similar proportions are shown in Table 12 for occupants of non-survivable mishap aircraft. Research conducted by Yoganandan et al. (2014) showed the pelvis loading duration affects injury location: more severe pelvis vertical accelerations, as indicated by shorter duration loading events, result in pelvic fractures; while longer loading duration results in fractures to vertebral levels superior to the pelvis (e.g., the lumbar spine). Results of the present study indicate that mishaps resulting in pelvic injuries were potentially more severe than those resulting in no pelvic injury.

Limitations

The results of the present study are based solely on entries in the USACRC aviation mishap database. Injury data for 217 injured occupants was not contained in the USACRC aviation mishap database. Additionally, study team members have participated in Army rotary-wing aviation mishap investigations during the study period as part of the USAARL Aviation Life Support Equipment Retrieval Program (ALSERP) (Voisine, Licina, & McEntire, 1997). Through their participation in ALSERP, authors have knowledge of at least one mishap that occurred in the 2012-2014 timeframe, during which spinal injuries meeting the study criteria were sustained by aircraft occupants; however, these injuries were not included in the aviation mishap database. Data from these injured occupants could influence the frequency and proportion of spinal and pelvic injuries. A review of the official mishap investigation files archived by the USACRC could allow researchers the opportunity to obtain critical information not contained in the aviation mishap database, allowing for greater accuracy in the overall study results.

All mishaps meeting the study inclusion criteria were used in computing the frequency of spinal injuries for the airframes of interest. Mishaps were not excluded based on kinematic parameters such as impact velocity, aircraft attitude at impact, impact angle, etc. Kinematic data such as those listed were not available for all mishaps meeting the basic inclusion criteria. For this reason, mishap aircraft survivability was used as a surrogate for mishap severity, assuming that occupants of survivable and partially survivable mishap aircrafts experienced similar acceleration levels that remained within human tolerance. The possibility exists that spinal injury frequency and rate could potentially be different if extremes of aircraft impact severity were excluded from the analysis.

Conclusions

The thoracolumbar portion of the spine continues to be the most injured portion of the spine in survivable and partially-survivable rotary-wing mishaps. Future research should investigate developing injury criteria based on thoracolumbar spinal injury tolerance. These injury criteria could then be used to develop performance requirements for the development of energy-absorbing, crashworthy seating for future rotary-wing airframes

The USACRC aviation mishap database has proven to be a useful resource for investigating injury trends and determining potential gaps in aviation safety that can be addressed through aeromedical research. A review of the actual accident files should also be carried out when possible to help augment data contained in the database and potentially provide a more accurate representation of injury trends.

Future Work

To investigate the influence of crashworthy seating on spinal injury risk, comparisons could be made between current crashworthy airframes and previous non-crashworthy airframes with similar mission types. The UH-60 and UH-1 airframes fulfill similar mission profiles and have similar seating configurations and capacities. Similarly, the AH-64 and AH-1 airframes could be compared, as both are attack aircraft with both occupants seated back-to-front along the centerline of the aircraft. Modern rotary-wing aircraft like the UH-60 and AH-64 are capable of higher performance than the aircraft they replaced, the UH-1 and AH-1, respectively. Examining spinal injuries between the modern and legacy would likely provide additional insight into the benefits of crashworthy seating.

References

Department of the Army, *Army Accident Investigations and Reporting*. DA PAM 385-40. Washington, DC: U.S. Secretary of the Army, March 18, 2015.

Department of the Army, *Seat System: Crash-Resistant, Non-Ejection, Aircrew, General Specification For*. MIL-S-58095A. St. Louis, MO: U.S. Army Aviation Systems Command, January 31, 1986.

Department of Defense, *Mishap Notification, Investigation, Reporting, and Record Keeping* (DoD Directive 6055.07). Washington D.C: U.S. Secretary of Defense for Acquisition, Technology, and Logistics, June 6. 2011

General Accounting Office (GAO) (now Government Accountability Office [GAO]). (1999). Military Personnel: Actions Needed to Better Define Pilot Requirements and Promote Retention. GAO/NSIAD-99-211, Washington D.C., August 1999.

Protection of Human Subjects, 32 C.F.R. § 219 (2013).

Shanahan, D. F. & Shanahan, M. O. (1989). Injury in U.S. Army Helicopter Crashes October 1979-September 1985. *The Journal of Trauma*, *29*(4), 415-422.

Voisine, J.J., Licina, J.R., & McEntire, B.J. (1997). *U.S. Army's Aviation Life Support Retrieval Program* (USAARL Report 97-16). Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory.

Yoganandan, N., Moore, J., Arun, M.W.J., & Pintar, F.A. (2014). Dynamic Responses of Intact Post Mortem Human Surrogates from Inferior-to-Superior Loading at the Pelvis. *Stapp Car Crash Journal*, *58*, 123-143.

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