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UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

Methodology and Considerations for Combining Historic Accelerative Loading Research to Update the U.S. Army Aeromedical Research Laboratory Head-Supported Mass Curve Using Survival Analysis

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EDO Determination and Number

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14. ABSTRACT

Military helmets are multi-functional tools that provide blunt and ballistic impact protection and are frequently used as a mounting platform for life support and operational enhancement technologies. The frequent use of these helmet-mounted technologies can increase the risk of cervical spine injury, both acute and chronic, to Warfighters due to the increase in head-supported mass (HSM) and changes in the location of the combined center of mass (CM) of the helmet and helmet-mounted technologies. Evidence of an increased neck injury risk was provided through epidemiological research. This evidence led the U.S. Army Aeromedical Research Laboratory (USAARL) to investigate and develop HSM requirements for Army rotary-wing helmets in 1997 (McEntire & Shannahan, 1997). Over the 25 years since the introduction of the USAARL HSM Curves, additional research has been conducted into the effects of HSM and HSM CM location.

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14. Abstract (continued)
The body of knowledge on the effects of HSM and CM location on performance and cervical spine injury generated over the previous 25 years was mined to identify data for refining the USAARL HSM Injury Curve. Survival analysis offers a means to re-analyze historical HSM research and update the USAARL HSM Injury guidance. Since the development of the USAARL HSM Injury Curve, survival analysis has become a commonplace statistical technique to generate probabilistic injury risk models (Petitjean & Trosseille, 2011; Yoganandan et al., 2016). Updated guidance on HSM and HSM CM location is needed to inform the design of head-supported devices optimized for use in the future Army aviation environment. This manuscript reviews the available HSM-related research and discusses the application of survival analysis to the historical data to develop an updated USAARL HSM Injury Curve.

Summary

Military helmets are multi-functional tools that provide blunt and ballistic impact protection and are frequently used as a mounting platform for life support and operational enhancement technologies. The frequent use of these helmet-mounted technologies can increase the risk of cervical spine injury, both acute and chronic, to Warfighters due to the increase in head-supported mass (HSM) and changes in the location of the combined center of mass (CM) of the helmet and helmet-mounted technologies. Evidence of an increased neck injury risk was provided through epidemiological research. This evidence led the U.S. Army Aeromedical Research Laboratory (USAARL) to investigate and develop HSM requirements for Army rotary-wing helmets in 1997 (McEntire & Shanahan, 1997). Over the 25 years since the introduction of the USAARL HSM Curves, additional research has been conducted into the effects of HSM and HSM CM location. The body of knowledge on the effects of HSM and CM location on performance and cervical spine injury generated over the previous 25 years was mined to identify data for refining the USAARL HSM Injury Curve. Survival analysis offers a means to re-analyze historical HSM research and update the USAARL HSM Injury guidance. Since the development of the USAARL HSM Injury Curve, survival analysis has become a commonplace statistical technique to generate probabilistic injury risk models (Petitjean & Trosseille, 2011; Yoganandan et al., 2016). Updated guidance on HSM and HSM CM location is needed to inform the design of head-supported devices optimized for use in the future Army aviation environment. This manuscript reviews the available HSM-related research and discusses the application of survival analysis to the historical data to develop an updated USAARL HSM Injury Curve.

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Background

Military helmets are multi-functional tools that provide blunt and ballistic impact protection. With increasing mission requirements, helmets are used as a mounting platform for life support and operational enhancement technologies, such as oxygen or gas masks and night vision goggles. The frequent use of helmet-mounted technologies increases the risk of cervical spine injury to Warfighters due to the increase in head-supported mass (HSM) and changes in the location of the combined center of mass (CM) of the helmet and helmet-mounted technologies. Stresses on the head and neck can be magnified by adding mass and increasing the CM offset away from the atlantooccipital complex (AOC), the head's pivot point on the spine. Ideally, as HSM can affect injury risk and performance, total HSM (i.e., mass of the helmet with all attached components) should be lightweight and balanced relative to the AOC to the greatest extent possible, with the helmet providing a comfortable fit for the entire mission duration.

Spine-associated symptomology and pathology have been a well-recognized health concern for military aviators and aircrew in both fixed- and rotary-wing platforms for over 50 years (Shanahan & Reading, 1985; Mason, 1995; Hamalainen et al., 1996; Hodgdon et al., 1997; Burton et al., 1999; Landau et al., 2006; Orsello et al., 2013). U.S. Army aviators are exposed to a host of potentially injurious events during an aviation crash, which includes but is not limited to, large vertical accelerations. Spinal pain from acute injuries and degeneration can lead to debilitating effects, even disqualifying some aviators from specific duties and continued military service. The possibility of post-injury rehabilitation for more severe injuries is very limited.

As early as 1989, a survey of U.S. and Australian military aircrew indicated concerns that flight helmets equipped with then-modern night vision goggles were too heavy (Crowley, 1992). Early research at the U.S. Army Aeromedical Research Laboratory (USAARL) investigated aircrew HSM because of its potential to impact health, readiness, and performance. Studies conducted at USAARL have found HSM alone is linked with decreased performance and increased injury risk (Butler, 1992; Alem et al., 1995; Ashrafiuon et al., 1998; Barazanji & Alem, 2000; Fraser et al., 2006). Fraser et al. (2006) reported that increased helmet weight and CM offset decrease flight performance and the ability to acquire visual targets quickly and accurately. This is supported by the work of Alem et al. (1995), who also found that target acquisition decreased with increased HSM when not in a simulator environment. Ashrafiuon et al. (1998) found that the addition of HSM proportionally adds to neck loading and that adjustments in CM offset could result in significantly higher forces under certain conditions. Barazanji and Alem (2000) and Butler and Alem (1997) found that mass and CM offset were associated with greater head accelerations and neck moments during whole-body vibration.

The increasing use of helmet-mounted displays (HMDs) led to concerns that Army aviators would be at an increased risk of cervical spine injury due to the increase in HSM associated with HMD use. Epidemiological research substantiated these concerns through the review and analysis of historic rotary-wing mishap reports. Shanahan and Shanahan (1989) revealed that spinal injuries occurred more frequently at the connection between the seventh cervical and first thoracic vertebrae (C7/T1 juncture) than any other part of the cervical or upper thoracic spine. This epidemiological evidence of a potential increased cervical spine injury risk drove the Reconnaissance and Attack Helicopter (RAH)-66 Comanche Program Office to request that USAARL investigate and develop HSM requirements for Army rotary-wing

helmets. This request ultimately led to the development and publication of guidance on allowable combinations of HSM and CM location (McEntire & Shanahan, 1997) (Figure 1).

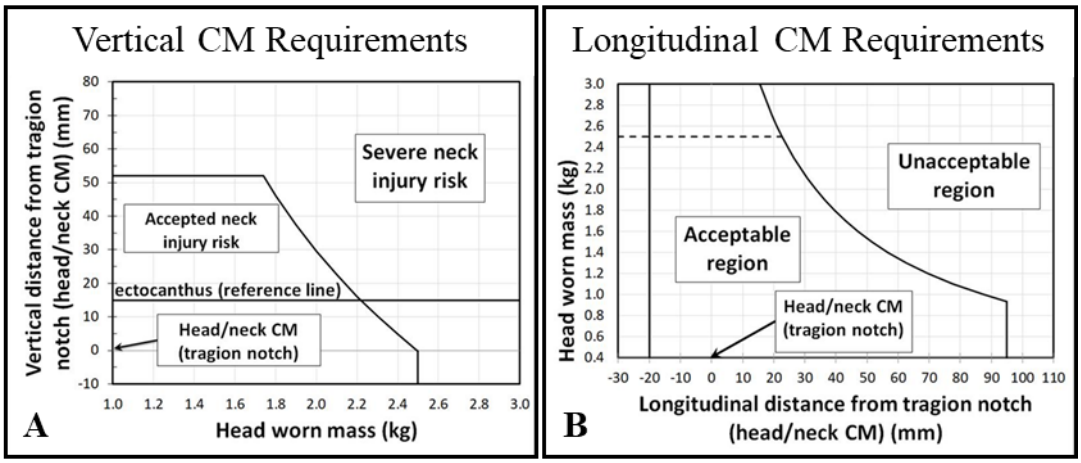

Figure 1. The USAARL HSM Curves developed for Army aviation environments. (A) The USAARL HSM Injury Curve uses the relationship between mass and vertical CM offset to describe acceptable ranges for mass properties relative to spine injury risk. (B) The USAARL HSM Performance Curve uses the relationship between mass and longitudinal CM offset to describe acceptable ranges for mass properties to minimize performance decrement.

The USAARL HSM Curves describe acceptable combinations of HSM and vertical CM location (Figure 1A) and HSM and longitudinal CM location (Figure 1B) for use in the Army aviation environment. The USAARL HSM Injury Curve, defining acceptable combinations of HSM and vertical CM offset (Figure 1A), was based on:

- the human cervical spine injury tolerance under tensile loads;
- anthropometric measurements from the U.S. Army aviation population of the time;
- the mass of the Attack Helicopter (AH)-1 Cobra helmet, which was the heaviest (worst-case) helmet in service at the time and which had not been associated with producing any cervical spine injuries during AH-1 mishaps; and
- an estimated worst-case acceleration exposure based on aircraft seat static and dynamic performance requirements (McEntire & Shanahan, 1997).

The USAARL HSM Performance Curve, defining acceptable combinations of HSM and longitudinal CM offset (Figure 1B), was based on human biomechanical response to whole-body vibration (Butler & Alem, 1997). Despite the names of the individual curves, vertical and longitudinal CM offsets can affect injury risk and/or performance.

Since their introduction in 1997, the USAARL HSM Curves have become the de facto standard for allowable HSM and HSM CM location used by rotary-wing helmet and HMD developers to prevent performance decrements and limit cervical spine injury risk among aviators. Over the 25 years since the introduction of the USAARL HSM Curves, additional research into the effects of HSM and HSM CM location has been conducted by USAARL, other Department of Defense (DoD) research laboratories, and academia. These research efforts have

investigated the effects of HSM and CM location on aviator and ground Soldier performance using human research volunteers (HRVs) under varying vibration exposures, and cervical spine injury using animal surrogates, post-mortem human surrogates (PMHSs), anthropomorphic test devices (ATDs), and computational modeling. Additionally, historic data gathered by the Naval Biodynamics Laboratory (NBDL) on the effects of non-contact, accelerative loading on HRVs has recently become accessible for injury biomechanics research through the USAARL Biodynamics Data Resource (BDR) (Schmidt et al., 2009; Olszko et al., 2022).

Updated guidance on HSM and HSM CM location is needed to guide the design of head-supported devices optimized for use in the future Army aviation environment. Advances in technology and knowledge regarding materials, electronics, and rotary-wing aircraft design are all being explored to provide the U.S. Army with combat advantages for future multi-domain operations (MDO). These technological advancements and the resulting increases in Army aviation aircraft flight performance will result in increased dynamic mechanical loadings on the aircrew while in flight and during mishap events.

This report describes (1) a review of HSM-related research conducted over the last 25 years to identify cervical spine injury-related data useful in updating the USAARL HSM Injury Curve and (2) the potential application of survival analysis to this historical dataset to update the USAARL HSM Injury Curve (Figure 1A), and (3) considerations for combining historical datasets.

Methods

Data Review

Over the last 25 years, USAARL has conducted or sponsored multiple studies investigating the influence of HSM on the risk of cervical spine injury. Data and reports generated by these internal and extramural studies were archived at USAARL and are available for review by USAARL researchers. Additionally, USAARL houses the BDR; the BDR contains data from thousands of non-contact accelerative loading trials involving HRVs (some of whom wore HSM) conducted at the NBDL.

USAARL's archive of historical datasets (i.e., BDR and internally- and extramurally-generated datasets) was examined to identify HSM-related injury research applicable for updating the USAARL HSM Injury Curve. Initially, datasets were examined for accelerative exposures representative of aviation mishaps with subject types that can provide sub-injurious and injurious responses. Subjects with and without HSM were considered. A dataset was considered applicable if exposure parameters (i.e., magnitude, duration, and direction) and cervical spine injury outcomes were documented, and if sufficient data were available to calculate a mass moment (as described in the Moment Calculations section of this report).

Additionally, a literature review was conducted to identify data to supplement data already available at USAARL. Peer-reviewed literature and DoD technical report archives were searched to identify manuscripts describing research into the effect of HSM on human performance and cervical spine injury risk. Each manuscript was reviewed to identify parameters such as the focus of the study (i.e., performance, injury, or both); the data source associated with the research (e.g., HRVs, animals, PMHSs, ATDs, computational models); the mass of the HSM

(also referred to as HSM magnitude) and HSM CM location; the exposure type (e.g., whole-body vibration, crash-type exposures), magnitude, duration, and direction (e.g., longitudinal, lateral, axial); and multiple other parameters. These parameters were entered into a database, which allowed the disparate studies to be compared and integrated based on the set of common parameters.

Moment Calculations

HSM magnitude, HSM CM location, and peak accelerative exposure level were used to calculate two different moments relative to the junction of the seventh cervical and first thoracic vertebrae (C7/T1 juncture), as described below.

Using the method described by McEntire and Shanahan (1997) to define the existing USAARL HSM Injury Curve (Figure 1A), HSM magnitude and CM location data were used to compute a mass moment for each dataset using Equation 1. In this equation, M is the mass moment (expressed in kilogram-centimeters [kg-cm]); m_{HSM}, m_{head}, and m_{neck} are the masses of the HSM, head, and neck (expressed in kilograms [kg]), respectively; and d_{HSM}, d_{head}, and d_{neck} are the vertical offsets from the C7/T1 juncture to the HSM CM, head CM, and cervical neck CM (expressed in centimeters [cm]), respectively.

$$\mathrm{M} = m_{HSM}d_{HSM} + m_{head}d_{head} + m_{neck}d_{neck} \qquad \text{(Equation 1)}$$

Because different datasets may define HSM CM location relative to different anatomical landmarks, the C7/T1 juncture was used as a common reference point for the analysis. This region of the cervical spine was noted by Shanahan and Shanahan (1989) as having sustained the largest number of fractures as a result of survivable and partially survivable Army helicopter mishaps and, therefore, was used by McEntire and Shanahan (1997) as the reference point for computing mass moments. Computing the mass moment about the C7/T1 juncture allows research studies investigating cervical spine injury without HSM to also be considered in the analysis; for these datasets, the m_{HSM} would be set to 0 kg, resulting in the mass moment being calculated based on the mass of the head and neck only.

A limitation of this mass moment method computation used by McEntire and Shanahan (1997) was that mass moment does not consider accelerative exposure. A new parameter, the accelerated mass moment (AMM), was also considered for analysis. The proposed parameter considers that the head, neck, and HSM are being equally exposed to an accelerative environment. Computation of the AMM parameter is defined by Equation 2 in which a is the peak magnitude of the accelerative exposure (expressed in meters per second squared [m/s^2]). As before, m_{HSM}, m_{head}, and m_{neck} are the masses (kg) of the HSM, head, and cervical neck, respectively, and r_{HSM}, r_{head}, and r_{neck} represent the radial distance (cm) between the C7/T1 juncture and the CMs of the HSM, head, and neck, respectively.

$$\mathrm{AMM} = a(m_{HSM}r_{HSM} + m_{head}r_{head} + m_{neck}r_{neck}) \qquad \text{(Equation 2)}$$

Radial distances were computed using the longitudinal (r_{long}) and vertical (r_{vert}) offsets of the HSM CM, head CM, and neck CM with respect to the C7/T1 juncture (Equation 3).

$$\mathrm{r} = \sqrt{{r_{long}}^2 + {r_{vert}}^2} \qquad \text{(Equation 3)}$$

Results

Data Review

USAARL's archive of historical datasets was examined to identify HSM-related injury research applicable for use in updating the USAARL HSM Injury Curve. Two stand-alone injury-focused studies were identified. The first study was conducted at USAARL and was focused on developing a thoracolumbar spinal injury criterion under vertical accelerative exposures. The second study was sponsored by USAARL and was conducted at the University of Virginia (UVA); this study investigated the influence of increased HSM on cervical spine injury risk. Finally, a single body of work conducted at the NBDL involving HRVs subjected to sub-injurious levels of accelerative exposure was identified for inclusion in this effort. A brief description of each study or body of work is described below.

USAARL male thoracolumbar spinal injury criteria.

USAARL collected data from 14 whole-body PMHSs subjected to vertical accelerations simulating a helicopter mishap event on a vertical acceleration tower (VAT); the intent of this research was to investigate thoracolumbar injury tolerance to vertical acceleration and provide injury-based performance metrics for energy-attenuating helicopter crew seats. To characterize the response of a specimen to accelerative exposures, each PMHS was instrumented with acoustic sensors, surface strain gages, accelerometers, and angular rate sensors rigidly mounted to vertebral bodies, pelvis, and head, and visual markers on the vertebral bodies. No HSM was added to the PMHS specimens during these tests.

VAT acceleration exposure parameters were determined to create carriage accelerative exposures representative of seat pan loading that an occupant could experience in an energy attenuating seat. Tests were conducted to measure accelerative loadings based upon the seat pan response specified by military specification MIL-S-58095A for crashworthy seat performance (Department of the Army, 1986). While peak acceleration and onset rate were modified to achieve the test conditions, the change in velocity remained constant at 42 feet per second (ft/s) for all tests. Test conditions and exposure parameters are shown in Table 1. Injuries to each PMHS specimen were determined from the post-test computed tomography (CT) scan and an autopsy by a board-certified forensic pathologist. Cervical spine injuries resulted from five of the 14 runs; cervical spine injuries resulting from these tests included vertebral body fractures, ligamentous injuries, and crushing of intervertebral discs. A summary of HSM, accelerative exposure, and injury outcome parameters related to USAARL's research is provided in Lafferty et al. (2020).

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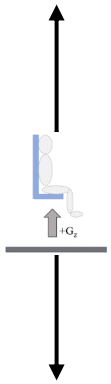
Table 1. Summary of HSM and Exposure Parameters Used in the USAARL Thoracolumbar Spinal Injury Study*

Dataset	HRV/ PMHS	Head-supported mass		Number of runs	Accelerative exposure							Resulted in cervical spine injury
		Added mass (kg)	Description		Direction	Description	Peak G	Onset (G/s)	Duration (ms)	Change in velocity (ft/s)	Device of insult	
USAARL	PMHS	NA	No HSM	4	+Z		22	1300-1500	NA	42	VAT at USAARL	Yes
	PMHS	NA	No HSM	3	+Z		22	1300-1500	NA	42	VAT at USAARL	No
	PMHS	NA	No HSM	2	+Z		22	900-1200	NA	42	VAT at USAARL	No
	PMHS	NA	No HSM	1	+Z		16	900-1200	NA	42	VAT at USAARL	Yes
	PMHS	NA	No HSM	4	+Z		16	900-1200	NA	42	VAT at USAARL	No
			Total VAT Runs	**14**								

*CG = center of gravity; ft/s = feet per second; G = acceleration due to gravity; G/s = acceleration due to gravity per second; HSM = head-supported mass; kg = kilogram; ms = millisecond; NA = not applicable; PMHS = post-mortem human surrogate; USAARL = U.S. Army Aeromedical Research Laboratory; VAT = vertical acceleration tower

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UVA cervical neck injury due to HSM.

In 2006, researchers from the UVA conducted six whole-body PMHS tests on a horizontal sled to assess the risk of cervical neck injury resulting from increased HSM. PMHS specimens were positioned in a 60-degree (°) reclined seat. Three HSM magnitudes of 0.0 kg (no HSM), 1.7 kg, and 2.0 kg were used. For tests involving HSM, the HSM location was co-located with the head CM. One run without HSM and one run with an HSM of 2.0 kg located at the head CM were run at a peak accelerative exposure level of 17 G. The remaining four runs were conducted with an HSM magnitude of 1.7 kg at peak accelerative exposures ranging from 15 to 31 G. Cervical spine injuries resulting from these tests included ligamentous injuries and crushing of intervertebral discs. A summary of HSM, accelerative exposure, and injury outcome parameters from the UVA study is provided in Table 2 (Bass et al., 2006).

NBDL body of work.

The former NBDL, located in New Orleans, LA, was in operation for 25 years studying, among other things, the dynamic response to whole-body, non-contact, inertial loading. HRVs participated in impact exposures of varying acceleration in the frontal (-X) and axial (+Z) directions on both horizontal and vertical accelerators. Subject- and sled-mounted sensors were used to collect acceleration data, and photo (i.e., high-speed film) data were used to capture the motion of both the subject and sled. A total of 163 HSM runs and 1613 non-HSM runs conducted on the horizontal and vertical accelerators were reviewed for this retrospective study. For the HSM runs, 22 healthy male HRVs, ranging in age from 19 to 28, received impact exposures from 2.77 to 9.16 G in the frontal (-X) and axial (+Z) directions. The range of mass added to the HRVs was 1.25 to 2.35 kg. The non-HSM runs consisted of 160 healthy, male HRVs, ranging in age from 17 to 38, receiving impact exposures from 1.95 to 15.91 G in the frontal (-X) and axial (+Z) directions. A summary of HSM, accelerative exposure, and injury outcome parameters from the NBDL body of work is provided in Table 3 (Muzzy et al., 1986; Schmidt et al., 2009; Olszko et al., 2022).

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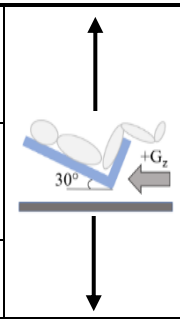
Table 2. Summary of HSM and Exposure Parameters Used in the UVA Cervical Neck Injury Study*

Dataset	HRV/ PMHS	Head-supported mass		Number of runs	Accelerative exposure							Resulted in cervical spine injury
		Added mass (kg)	Description		Direction	Description	Peak G	Onset (G/s)	Duration (ms)	Change in velocity (ft/s)	Device of insult	
UVA	PMHS	2.0	2.0 kg at Head CG with Halo Device	1	+XZ		17	NA	NA	33	Horizontal accelerator	Yes
	PMHS	1.7	1.7 kg at Head CG with Halo Device	4	+XZ		15-31	NA	NA	30-43	Horizontal accelerator	Yes
	PMHS	NA	No HSM	1	+XZ		17	NA	NA	33	Horizontal accelerator	Yes
			Total UVA Runs	**6**								

*CG = center of gravity; ft/s = feet per second; G = acceleration due to gravity; G/s = acceleration due to gravity per second; kg = kilogram; ms = millisecond; NA = not applicable; PMHS = post-mortem human surrogate; UVA = University of Virginia

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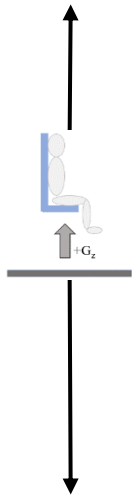
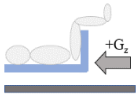
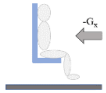
Table 3. Summary of HSM and Exposure Parameters Used in NBDL Accelerative Exposure Research*

Dataset	HRV/ PMHS	Head-supported mass		Number of runs	Accelerative exposure							Resulted in cervical spine injury
		Added mass (kg)	Description		Direction	Description	Peak G	Onset (G/s)	Duration (ms)	Change in velocity (ft/s)	Device of insult	
NBDL	HRV	NA	Unhelmeted	1	+Z		3.13	59	305	18	VAT at NBDL	No
	HRV	1.25	Frame+ Skullcap	14	+Z		2.79-9.01	92-128	261-282	27-32	VAT at NBDL	No
	HRV	1.55	0.3 kg at eye level	17	+Z		2.92-9.06	117-185	235-264	32-40	VAT at NBDL	No
	HRV	1.85	0.6 kg at eye level	17	+Z		2.87-9.04	NA	NA	NA	VAT at NBDL	No
	HRV	1.55	0.3 kg at 45°	14	+Z		2.77-9.04	NA	NA	NA	VAT at NBDL	No
	HRV	1.85	0.6 kg at 45°	15	+Z		2.92-9.11	NA	NA	NA	VAT at NBDL	No
	HRV	1.75	0.5 kg at Top of Head	13	+Z		2.94-9.16	NA	NA	NA	VAT at NBDL	No
	HRV	1.80	0.275 kg at 45° and 135°	16	+Z		3.03-9.00	NA	NA	NA	VAT at NBDL	No
	HRV	2.35	0.550 kg at 45° and 135°	19	+Z		2.94-9.12	NA	NA	NA	VAT at NBDL	No
	HRV	NA	No HSM	205	+Z		1.95-12.25	NA	NA	NA	VAT at NBDL	No
	HRV	NA	No HSM	380	+Z		2.0-12.25	NA	NA	NA	HA at NBDL	No
	HRV	1.25	Frame+ Skullcap	37	-X		3.00-9.14	53-227	220-312	18-43	VAT at NBDL	No
	HRV	NA	No HSM	1028	-X		1.95-15.91	148-1095	6-1040	13-38	HA at NBDL	No
	Total NBDL Runs			**1776**								

*ft/s = feet per second; G = acceleration due to gravity; G/s = acceleration due to gravity per second; HA = horizontal accelerator; HRV = human research volunteer; HSM = head-supported mass; kg = kilogram; ms = millisecond; NA = not applicable; NBDL = Naval Biodynamics Laboratory; PMHS = post-mortem human surrogate; VAT = vertical acceleration tower

Literature review results.

The literature review examined publicly available HSM data as published in peer-reviewed journals and DoD technical reports. Eighty (80) studies were identified in this review. Common parameters were collected from each study. A list of the 80 studies, including the citation, year published, data focus (e.g., injury or performance), and data type (e.g., PMHS, HRV, ATD), is presented in Table A1.

Within this body of HSM-related literature, 63 studies focused on investigating cervical spine injury with and without HSM under accelerative exposures. Fourteen (14) studies focused on investigating the influence of HSM on performance. Three (3) studies investigated the effects of HSM on both injury and performance.

Applying Survival Analysis to HSM Data

Survival analysis description.

In recent years, the statistical technique of survival analysis has been used in the study of injury biomechanics to generate probabilistic risk of injury models or injury risk curves (IRCs) (Petitjean & Trosseille, 2011; Yoganandan et al., 2016). In general, IRCs consider a continuous biomechanical metric (e.g., mass moment or AMM) as the independent variable for which there is an associated risk of injury at every value of the domain (metric). The use of survival analysis to generate IRCs is preferred over other probabilistic models, such as binary logistic regression, due to the ability to include censored data (Begeman & Aekbote, 1996; Petitjean & Trosseille, 2011), consider additional independent variables as covariates in the analysis, and analyze both continuous and categorical data using covariates.

Censored data are data for which there is only partial information known. Censoring provides information on whether the magnitude of the independent (predictor) variable is known for the precise time at which failure (e.g., ligament tearing, fracture) occurs. There are four types of censoring: uncensored, right-censored, left-censored, and interval-censored.

- An uncensored data point is a data point where the magnitude of the independent variable corresponding to the instance of failure is known.
- A right-censored data point is associated with a non-failure case; since a failure did not occur, a right-censored data point is a data point where the magnitude of the independent value at the instant of failure cannot be known. The magnitude of the independent variable needed to cause a failure is larger (i.e., further to the right on a number line) than the magnitude associated with the non-failure.
- A left-censored data point is a data point where a failure occurs but the magnitude of the independent variable at the instant of failure is not known. The magnitude at which the failure occurred may be lower than the known magnitude of the independent variable (i.e., further to the left on a number line).
- An interval-censored data point is a data point where a failure occurs between two known magnitudes of the independent variable.

The precise timing of an injury cannot always be determined; therefore, the precise value of the independent (predictor) variable (e.g., mass moment) also cannot be determined. The ability of survival analysis to account for censored data is one reason survival analysis is becoming the preferred method for developing IRCs.

Additionally, survival analysis techniques for IRCs allow for the inclusion of additional subject- or test-specific parameters (e.g., age, sex, bone mineral density, peak accelerative exposure level, mass moment) to be used as covariates (Yoganandan, Arun, et al., 2015; Yoganandan, Banerjee, et al., 2015; Yoganandan et al., 2018). The use of covariates can help account for variability within the dataset and help remove confounder bias by adjusting for differences between groups. While the independent variable of interest is always continuous, covariates can be continuous or categorical.

The data available in the USAARL, UVA, and NBDL research described above lend themselves well to survival analysis as the datasets can be used to compute continuous metrics of interest, such as mass moment and AMM, and other independent variables, such as peak accelerative exposure, can be extracted and considered as a covariate. Injury outcome data are also available for each dataset for use as the dependent variable.

Example survival analysis case.

A description of how survival analysis could be applied to data from historical datasets to determine limits on allowable combinations of HSM magnitude and HSM CM location (like that shown in Figure 1A) is provided below. Exemplar data from the USAARL, UVA, and NBDL datasets will be used to illustrate potential issues that may be encountered when integrating historical datasets.

Prior to conducting survival analysis, the independent variables to be considered must be identified. The USAARL, UVA, and NBDL datasets all have multiple important independent variables that could affect injury outcomes. These include HSM magnitude, HSM CM location, and peak accelerative exposure (Table 1 - Table 3). Any of these independent variables could be used as the predictor variable in the survival analysis, with the others included as covariates. To simplify the analysis (i.e., to reduce the number of inputs to the survival analysis) these independent variables could be used to compute mass moments or AMMs for each test using the equations shown earlier.

Additionally, the dependent variable of interest must also be identified. Since this example deals with identifying the influence of HSM on cervical spine injury, the dependent variable would be cervical spine injury occurrence (e.g., yes or no); for the purposes of the example, an HRV or PMHS specimen was considered injured if ligamentous injuries (e.g., tears, transections), intervertebral disc compression, or vertebral fractures occurred at or above the C7/T1 juncture because of the accelerative exposure (Table 1 - Table 3). Otherwise, the HRVs or PMHS specimens were considered uninjured even if these types of injuries occurred at vertebral levels below the C7/T1 juncture.

The upcoming paragraphs describe how mass moment, peak accelerative exposure, and injury outcomes would be input into a survival analysis and how the models produced by survival analysis could be implemented to define acceptable combinations of HSM magnitude and HSM CM for different accelerative exposure levels.

In this survival analysis example, the continuous independent predictor would be mass moment. The dependent variable would be cervical spine injury outcome expressed as a binary variable representing the occurrence of cervical spine injury (i.e., 0 for no injury and 1 if an injury occurred). The censoring status of the mass moment values would also need to be accounted for in the analysis. Using the definitions provided above, all mass moment values associated with non-injury data would be right-censored. As the exact mass moment associated with injury cases would be known, the values of mass moment associated with injury would be considered as uncensored values. The peak accelerative exposures associated with each trial could also be entered as an additional descriptor of the data (covariates).

For each trial considered in the analysis, mass moment, mass moment censoring information, peak accelerative exposure, and injury outcome would be tabulated into an input file for the survival analysis. In this example, the survival analysis would then generate a model of the input data (i.e., the family of curves) predicting risk of cervical spine injury based on mass moment and level of peak accelerative exposure (Figure 2). The example output shows injury risk functions for peak accelerative exposure levels of 5, 10, 15, 20, 25, and 30 G.

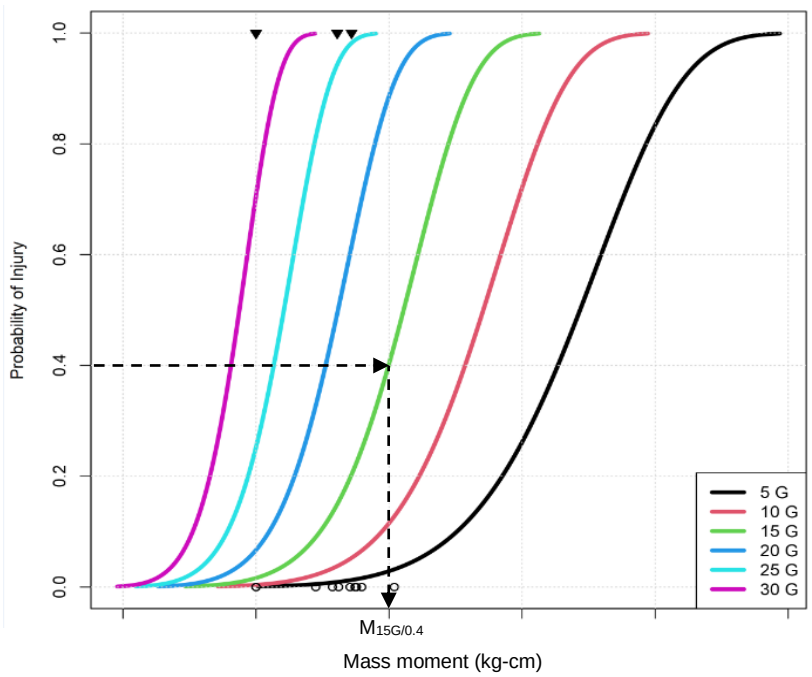


Figure 2. Exemplar plot of survival analysis models depicting risk of injury as a function of mass moment (independent variable) and peak accelerative exposure. $M_{15G/0.4}$ represents the mass moment corresponding to a probability of injury of 40 percent at a peak accelerative exposure of 15 G.

From these models (Figure 2), a mass moment can be determined given an allowable probability of injury and knowledge of the potential accelerative exposure environment. If a 40 percent probability of injury is considered to be acceptable and personnel wearing the HSM system (e.g., helmet, night vision devices) could be exposed to a peak accelerative exposure of 15 G, the allowable mass moment about the C7/T1 juncture would be $M_{15G/0.4}$ as shown in Figure 2. From this value, combinations of HSM magnitude and HSM CM location can be computed by assuming a range of HSM magnitudes and calculating the corresponding HSM locations relative to the C7/T1 junction.

A similar analysis could be conducted using AMM (Equation 2) as the independent predictor variable and injury outcome as the dependent variable. Like mass moment, the value of AMM at the time an injury occurred would be known, and therefore, the AMM values would be considered uncensored. The use of AMM simplifies the survival analysis by not introducing covariates. As with mass moment, AMM combines HSM magnitude and HSM CM location into a continuous variable, but AMM is also a function of peak accelerative exposure; therefore, AMM combines all the metrics of interest into a single variable of interest.

Discussion

Combining datasets can allow factors that could not be considered in a single-dataset analysis to be investigated. When considered alone, the USAARL data would only be applicable to determining an acceptable HSM magnitude and HSM CM location for accelerative exposures of 16 to 22 G (Table 1). Similarly, data from UVA would only be applicable to accelerative exposures of approximately 15 to 31 G (Table 2), and NBDL data would be applicable to low level exposures of approximately 2 to 12 G (Table 3). When used together, the multiple datasets potentially allow for guidance to be developed over a more comprehensive range of accelerative exposures, making them applicable to a range of Warfighter operational exposures.

While combining datasets can offer advantages, integration of datasets is non-trivial, and several factors need to be considered when combining datasets generated at different times or by different research groups. Three major considerations are discussed below.

Dissimilar Reporting of Mass Properties Data

Different research organizations may express their HSM CM locations relative to different anatomical regions. For example, UVA defined HSM CM location relative to the head center of gravity (CM) (Table 2). NBDL defined HSM CM locations with respect to multiple locations including the top of the head, the eyes, and at angles relative to a horizontal plane (Table 3). To integrate the two datasets for analysis, all HSM CM locations must be expressed relative to a common anatomic reference like the C7/T1 juncture chosen by McEntire and Shanahan (1997) prior to using them in any survival analysis.

The use of dissimilar mass properties (i.e., HSM magnitude and HSM CM location) measurement and reporting techniques can confound a combined analysis. Even within the DoD, mass properties are measured and reported differently between DoD research laboratories. To address this issue within the Army, USAARL and the U.S. Army Combat Capabilities Development Command Soldier Center (DEVCOM SC) collaborated on developing an Army-

wide standard for mass properties data collection and reporting (Flath et al., 2020). The effort produced a proposed standard that defines a common fixture for mounting head-supported devices to mass properties measurement instruments, a standard method for conducting mass properties measurements, and a standard anatomic reference point (Tragion Notch) for reporting mass properties information (Flath et al., 2020). The proposed standard will be used Army-wide and is being considered for adoption by other branches of the DoD.

Subject Types

Datasets are often difficult to combine due to the subjects tested. Studies conducted by USAARL and UVA used PMHS specimens (Table 1 & Table 2); these two studies provided important information on cervical spine injury with and without HSM. NBDL data were collected using HRVs (Table 3), and all trials were non-injurious. As noted earlier, combining the three datasets provides information across a continuum of accelerative exposure; combining the three datasets also allows no injury and injury conditions to be evaluated. However, the PMHS cervical spine has been shown to be weaker than that of a living human; Chancey et al. (2003) showed that ligamentous failure in PMHS tensile tests underestimates cervical spine strength by a factor of 2.85. Combining the three historical datasets without accounting for the differences in living human and PMHS response through techniques such as scaling may result in conservative, and potentially overly restrictive, guidance on allowable combinations of HSM magnitude and HSM CM location.

Female Soldiers represent a large part of the active Army. As of October 2022, female Soldiers made up 15.7 percent of the active Army (U.S. Army G-1, 2022). However, almost all HSM-related injury research has been gathered on male HRVs and PMHS specimens. The risk of cervical spine injury related to HSM will likely be different for females due to the difference in cervical neck morphology, range of motion (ROM), and strength, as compared to males. More research into the effects of HSM on females is needed to address these potential differences. USAARL has an ongoing study involving female PMHS specimens subjected to vertical accelerative exposures; however, HSM is not a parameter being investigated. Even so, cervical spine injuries may still result from these exposures despite the lack of HSM (Lafferty et al., 2020). If so, results from this study can potentially be combined with female data extracted from the body of HSM-related work described in the manuscripts listed in Table A1 in a future analysis to develop female-specific guidance on HSM magnitude and HSM CM location.

Accelerative Exposure Reference Frame

When integrating multiple datasets, the reference frame in which the accelerative exposure information is presented must be known. The USAARL, UVA, and NBDL datasets defined the accelerative exposures in terms of sled or carriage accelerations; the accelerative exposures were inputs to the HRVs or PMHS specimens. Previous HSM research involving HRVs has characterized the accelerative exposure differently (Shivers et al., 2018). In this work, HRVs performed common infantry Soldier tasks while wearing different HSM configurations; the acceleration exposure for the HRVs was characterized in terms of accelerations measured at the helmet during each task (Shivers et al., 2018). These accelerative exposures were not an input measure but rather a response measure. For accelerative exposures to be combined in an analysis, all exposures must be expressed in the same reference frame.

Conclusions and Recommendations

Integrating data from previous historical studies is non-trivial. However, if issues related to the considerations mentioned previously (i.e., dissimilar reporting of mass properties, subject types, and accelerative exposure reference frames) can be addressed, combining multiple datasets can potentially allow for an expanded analysis to be performed.

Survival analysis should be considered in future analysis of these combined datasets. Survival analysis allows censored and uncensored data to be considered in the analyses, potentially increasing the accuracy of the resulting models, and allows for multiple independent variables to be analyzed using covariates. Also, survival analysis relates the magnitude of an independent predictor variable to risk of injury, which could allow guidance on allowable HSM to be based on acceptable risk of injury.

The following recommendations are made based on the results of this work:

- Recommend that all branches of the DoD develop a common methodology for measuring and reporting HSM data. The Army has developed a standard for the measurement and reporting of HSM data. Sister Services should consider adopting this standard to allow consistent HSM data measurement and reporting across DoD research laboratories.
- More research into the effects of HSM on females should be conducted. Female Soldiers account for 15.7 percent of the active Army (U.S. Army G-1, 2022). Previous HSM-related injury research has been gathered primarily on males. The risk of cervical spine injury related to HSM will likely be different for females due to the difference in cervical neck morphology, ROM, and strength, as compared to males.

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Mason, K. T., Harper, J. P., & Shannon, S. G. (1995). *U.S. Army aviation epidemiology data register: Incidence and age-specific rates of herniated nucleus among U.S. Army aviators, 1987-1992* (Report No. 95-33). U.S. Army Aeromedical Research Laboratory.

McEntire, B. J., & Shanahan, D. F. (1997). *Mass requirements for helicopter aircrew helmets* (Report No. 98-14). U.S. Army Aeromedical Research Laboratory.

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Olszko, A. V., Beltran, C. M., Vasquez, K. B., & Chancey, V. C. (2022). *Expansion of the biodynamics data resource (BDR): Non-human primate impact acceleration research data in the BDR* (USAARL-TECH-FR--2022-30). U.S. Army Aeromedical Research Laboratory.

Orsello, C. A., Phillips, A. S., & Rice, G. M. (2013). Height and in-flight low back pain association among military helicopter pilots. *Aviation, Space, and Environmental Medicine, 84*(1), 32–7.

Petitjean, A., & Trosseille, X. (2011). *Statistical simulations to evaluate the methods of the construction of injury risk curves* (Report No. 2011-22-0015). SAE Technical Paper.

Schmidt, A. L., Austermann, A. E., Vasquez, K. B., Shender, B. S., & Chancey, V. C. (2009). *Establishing the biodynamics data resource (BDR): Human volunteer impact acceleration research data in the BDR* (Report No. 2010-01). U.S. Army Aeromedical Research Laboratory.

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Appendix A. Summary of HSM-related Literature Identified

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Table A1. Summary of HSM-related Literature

Citation	Year published	Study focus	Data source
Williams, S. T., Madison, A. M., & Chancey, V. C. (2022). *Defining normal cervical spine range of motion in rotary-wing pilots (part 2): A method of estimating UH-60 aviator cervical spine range of motion using head position data from an optical-based inertial tracker* (USAARL-TECH-FR--2022-34). U.S. Army Aeromedical Research Laboratory.	2022	Performance	HRV
Brozoski, F. T., Chancey, V. C., Licina, J. R., & McEntire, B. J. (2020). *Retrospective review of spinal injuries in U.S. Army rotary-wing mishaps: January 1990-December 2014* (USAARL-TECH-FR--2020-024). U.S. Army Aeromedical Research Laboratory.	2020	Injury	Epidemiology
Lafferty, E., Daniel, R., Logsdon, K., Flath, N., Fralish,V., Mazuchowski, E., Chancey, V. C., & McEntire, B. J. (2020). *Injury assessement reference values for the spine under vertical loading* (USAARL-TECH-FR--2020-051). U.S. Army Aeromedical Research Laboratory.	2020	Injury	PMHS/ATD
Dargie, A., Olsko, A., Beltran, C., McGhee, J., Dorman, D., Vasquez, K., Shender, B., & Chancey, V. (2018, May). *Analysis of EMG and symptoms of human volunteers in the impact acceleration program at the Naval Biodynamics Laboratory* [Oral Presentation]. Aerospace Medical Association (AsMA) Annual Scientific Meeting, Dallas, TX, United States.	2018	Injury/ performance	HRV
Jadischke, R., Viano, D. C., McCarthy, J., & King, A. I. (2016). The effects of helmet weight on hybrid III head and neck responses by comparing unhelmeted and helmeted impacts. *Journal of Biomechanical Engineering*, *138*(10), 101008.	2016	Injury	ATD
Gaur, S. J., Joshi, W., Aravindakshan, B., & Aravind, A. S. (2013). Determination of helmet CG and evaluation of neck injury potentials using "Knox Box criteria" and neck torque limits. *Indian Journal of Aerospace Medicine, 57*(1), 37–44.	2013	Injury	ATD
Parr, M. J. C., Miller, M. E., Bridges, N. R., Buhrman, J. R., Perry, C. E., & Wright, N. L. (2012). Evaluation of the Nij neck injury criteria with human response data for use in future research on helmet mounted display mass properties. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 56, No. 1, pp. 2070-2074).	2012	Injury	HRV/ mathematical model
Manoogian, S. J., Kennedy, E. A., & Duma, S. M. (2005). *A literature review of musculoskeletal injuries to the human neck and the effects of head-supported mass worn by Soldiers* (Report No. CR-2006-01). U.S. Army Aeromedical Research Laboratory.	2006	Injury/ performance	Epidemiology/ literature review
Bass, C. R., Donnellan, L., Salzar, R., Lucas, S., Folk, B., Davis, M., Rafaels, K., Planchak, C., Meyerhoff, K., & Ziemba, A. (2006). A new neck injury criterion in combined vertical/frontal crashes with head supported mass. *Proceedings of the IRCOBI Conference* (pp. 20-22).	2006	Injury	PMHS
Manoogian, S. J., Kennedy, E. A., Wilson, K. A., Duma, S. M., & Alem, N. M. (2006). Predicting neck injuries due to head-supported mass. *Aviation, Space, and Environmental Medicine*, *77*(5), 509–514.	2006	Injury	Computational model
Alem, N., & Fraser, S. (2006). Effects of head-supported mass on pilot performance during UH-60 flight simulations. *Aviation, Space, and Environmental Medicine, 77*(3), 468.	2006	Performance	HRV
Halldin, P., Hedenstierna, S., von Holst, H., & Brolin, K. (2006). *Finite element analysis of the effects of head-supported mass on neck responses: Complete phase three report*. U.S. Army European Research Office.	2006	Injury	Computational model
Fraser, S., Alem, N., & Chancey, V. C. (2006). Helicopter flight performance with head-supported mass. *Annual Forum Proceedings-American Helicopter Society* (Vol. 62, No. 3, p. 1903).	2006	Performance	HRV
Kleinberger, M. (2005). *Critical review of low severity neck injury in Army aircrew* [Unpublished manuscript].	2005	Injury	Epidemiology/ literature review
Merkle, A. C., Kleinberger, M., & Uy, O. M. (2005). The effects of head-supported mass on the risk of neck injury in army personnel. *Johns Hopkins APL Technical Digest*, *26*(1), 75–83.	2005	Injury	ATD
Merkle, A. C. (2005). *Effects of head-supported mass on pilot performance: A statistical analysis of USAARL simulated flight data* [Unpublished manuscript].	2005	Performance	HRV
Halldin, P. (2005). *Finite element analysis of the effects of head-supported mass on neck responses: Complete phase two report* [Unpublished manuscript].	2005	Injury	Computational model
Thuresson, M., Linder, J., & Harms-Ringdahl, K. (2003). Neck muscle activity in helicopter pilots: Effect of position and helmet-mounted equipment. A*viation, Space, and Environmental Medicine, 74*(5), 527–532.	2005	Performance	HRV
Kennedy, E. (2004). *Biodynamic simulations of musculoskeletal injuries to the human neck due to added head-supported mass worn by Soldiers in military environments* [Unpublished manuscript].	2004	Injury	Computational model

Citation	Year published	Study focus	Data source
Merkle, A. (2004). *Effects of head-supported mass on Hybrid III response during simulated ground vehicle crashes* [Unpublished manuscript].	2004	Injury	ATD
Bass, C. R, Salzar, R., Donnellan, L., & Lucas, S. (2004). *Injury risk from HSM loading (HM 2,3,4,5 series)* [Unpublished manuscript].	2004	Injury	PMHS
Doczy, E., Mosher, S., & Buhrman, J. (2004, September). The effects of variable helmet weight and subject bracing on neck loading during frontal-Gx impact. *Proceedings of the 42nd Annual SAFE Symposium* (pp. 186-192). SAFE Association.	2004	Injury	HRV/ computational model
Paskoff, G. R., & Sieveka, E. (2004). Influence of added head mass properties on head/neck loads during standard helicopter impact conditions. *Proceedings of the 42nd Annual SAFE Symposium* (pp. 20-40). SAFE Association.	2004	Injury	ATD
Halldin, P., Brolin, K., Hedenstierna, S., Aare, M., & von Holst, H. (2004). *Finite element analysis of the effects of head-supported mass on neck responses: Complete phase one report* (N62558-03-C-0013) U.S. Army European Research Office.	2004	Injury	Computational model
Alem, N. (2004). *Target acquisition by pilots wearing various head-supported masses during simulated flight* [Unpublished manuscript].	2004	Performance	HRV
Perry, C. E., Buhrman, J. R., Doczy, E. J., & Mosher, S. E. (2003). *Evaluation of the effects of variable helmet weight on human response during lateral+ Gy impact* (Report no. AFRL-HEWP-TR-2004-0013). U.S. Air Force Research Laboratory.	2003	Performance	HRV/ATD
Paskoff, G. R. (2002). *Head-supported mass crash testing* [Unpublished manuscript].	2002	Injury	ATD
Bass, C. R., Salzar, R., Davis, M., Bolton, J., Van Rooij, L., & Duma, S. (2002). *Neck injuries form HSM loading (1 series)* [Unpublished manuscript].	2002	Injury	PMHS
Barazanji, K. W., & Alem, N. M. (2000). *Effects of head-supported devices on female aviators during simulated helicopter rides* (Report No. 2000-16). U.S. Army Aeromedical Research Laboratory.	2000	Performance	HRV
McEntire, B. J. & Shanahan, D. F. (1998). *Mass requirements for helicopter aircrew helmets* (Report No. 98-14). U.S. Army Aeromedical Research Laboratory.	1998	Injury/ performance	Mathematical model
Brozoski, F. T., Mobasher, A. A., McEntire, B. J., & Alem, N. M. (1998). Mass and location criteria of head-supported devices using articulated total body simulations. *Current Aeromedical Issues in Rotary Wing Operations*, 19.	1998	Injury	Computational model
Perry, C. E. (1998). Effect of helmet inertial properties on male and female head response during+ Gz impact accelerations. *SAFE Journal*, *28*(1), 32–38.	1998	Injury	HRV
Margulies, S. S., Yuan, Q., Guccione Jr, S. J., & Weiss, M. S. (1998). Kinematic response of the neck to voluntary and involuntary flexion. *Aviation, Space, and Environmental Medicine, 69*(9), 896–903.	1998	Sub-injury	HRV
Butler, B. P., & Alem, N. M. (1997). *Long-duration exposure criteria for head-supported mass* (Report No. 97-34). U.S. Army Aeromedical Research Laboratory.	1997	Performance	HRV
Shannon, S. G., & Mason, K. T. (1998). *U.S. army aviation life support equipment retrieval program: Head and neck injury among night vision goggle users in rotary-wing mishaps* (Report No. 98-02). U.S. Army Aeromedical Research Laboratory.	1997	Injury	Epidemiology
Ashrafiuon, H., Alem, N. M., & McEntire, B. J. (1997). Effects of weight and center of gravity location of head-supported devices on neck loading. *Aviation, Space, and Environmental Medicine*, *68*(10), 915–922.	1997	Injury	Computational model
Alem, N., Meyer, M. D., & Albano, J. P. (1995). *Effects of head supported devices on pilot performance during simulated helicopter rides* (Report No. 95-37). U.S. Army Aeromedical Research Laboratory.	1995	Performance	HRV
Guccione Jr, S. J., & Weiss, M. S. (1995). The reliability of human head/neck force and torque estimation. *SAE Transactions*, 3043–3064.	1995	Sub-injury	HRV
Thunnissen, J., Wismans, J., Ewing, C. L., & Thomas, D. J. (1995). Human volunteer head-neck response in frontal flexion: A new analysis. *SAE Transactions*, 3065–3086.	1995	Injury	HRV/PMHS
Lambert, J., & Guccione, S. (1995). *Linear regression analysis of human and manikin head kinematic response to +Gz impact acceleration* (Report No. NBDL-95R004). Naval Biodynamics Laboratory.	1995	Injury	HRV/ATD
Matson, D., Weiss, M., & Prell, A. (1995). *Human neck elongation in response to indirect frontal impact acceleration* (Report No. 95D004). Naval Biodynamics Laboratory.	1995	Sub-injury	HRV
Perry, C. E. (1994). *Vertical impact testing of two helmet-mounted night vision systems* (Report No. AL/CF-SR-1994-0013). Air Force Research Laboratory.	1994	Injury	ATD
Buhrman, J. R., & Perry, C. E. (1994). Human and manikin head/neck response to+ Gz acceleration when encumbered by helmets of various weights. *Aviation, Space, and Environmental Medicine*, *65*(12), 1086–1090.	1994	Injury	HRV/ATD
Thunnissen, J. (1994). *Omni-directional head-neck response defining response corridors. Part 1: Data-processing of the volunteer data* (Report No. 95.OR.BV1/JTH). Dutch Organization for Applied Scientific Research.	1994	Injury	PMHS/HRV

Citation	Year published	Study focus	Data source
Perry, C. E., Buhrman, J. R., & Knox III, F. S. (1993). Biodynamic testing of helmet mounted systems. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 37, No. 1, pp. 79-83). Sage Publications.	1993	Injury	Epidemiology
Butler, B. P. (1992). *Helmeted head and neck dynamics under whole-body vibration* (Publication No. 9303701) [Doctoral dissertation, University of Michigan]. ProQuest Dissertations.	1992	Performance	HRV
Alem, N. M., Shanahan, D. F., Barson, J. V., & Muzzy, W. H. (1991). *The airbag as a supplement to standard restraint systems in the AH-1 and AH-64 attack helicopters and its role in reducing head strikes of the copilot/gunner* (Report No. 91-6, Vol. I). U.S. Army Aeromedical Research Laboratory.	1991	Injury	ATD
Alem, N. M., Shanahan, D. F., Barson, J. V., & Muzzy, W. H. (1991). *The airbag as a supplement to standard restraint systems in the AH-1 and AH-64 attack helicopters and its role in reducing head strikes of the copilot/gunner* (Report No. 91-6, Vol. II). U.S. Army Aeromedical Research Laboratory	1991	Injury	ATD
Weiss, M. S., & Guccione, S. J. (1990). A kinematic/dynamic model for prediction of neck injury during impact acceleration. In *Advisory Group for Aerospace Research and Development, Neck Injury in Advanced Military Aircraft Environments* (SEE N 90-25459 19-52).	1990	Injury	Computational model
Muzzy III, W. H., Bittner Jr, A. C., & Willems, G. C. (1986). Safety evaluation of helmet and other mass additions to the head. *Proceedings of the Human Factors Society Annual Meeting, 30*(13), 1301–1305.	1986	Sub-injury	HRV
Muzzy III, W. H., Seemann, M. R., Willems, G. C., Lustick, L. S., & Bittner Jr, A. C. (1986). The effect of mass distribution parameters on head/neck dynamic response. *SAE Transactions*, 716–732.	1986	Sub-injury	HRV
Weiss, M. S. L., & Leonard, S. (1986). *Guidelines for safe human experimental exposure to impact acceleration* (Report No. NBDL-86R006). Naval Biodynamics Laboratory.	1986	Sub-injury	HRV
Wamsley, B. W., Bittner Jr, A. C., Gilbert, N. S., & Lustick, L. S. (1986). *Dynamic variable and temporary injury correlation for human head and neck impact experiments* (Report No. NBDL-86R007). Naval Biodynamics Laboratory.	1986	Sub-injury	HRV
Seemann, M. R., Muzzy, W. H., & Lustick, L. S. (1986). *Comparison of human and Hybrid III head and neck dynamic response* (Report No. 861892). SAE International, Inc.	1986	Injury	HRV/ATD
Becker, E. (1985). *Linkage motion* (Report No. 15716). QEI, Incorporated.	1985	Injury	Computational model
Becker, E. (1985). *Rigid body motion* (Report No. 15715). QEI, Incorporated.	1985	Injury	Computational model
Becker, E. (1985). *Simulation studies* (Report No. 15717). QEI, Incorporated.	1985	Injury	Computational model
Bowman, B. M., Schneider, L. W., Lustick, L. S., Anderson, W. R., & Thomas, D. J. (1984). Simulation analysis of head and neck dynamic response. *SAE Transactions*, 941–973.	1984	Injury	Computational model
Seemann, M. R., Lustick, L. S., & Frisch, G. D. (1984). Mechanism for control of head and neck dynamic response. *SAE Transactions*, 974–989.	1984	Sub-injury	HRV
Heardon, B. F., Brinkley, J. W., Hudson, D. M., & Saylor, W. J. (1983). *Effects of a negative G strap on restraint dynamics and human impact response* (Report No. AFAMRL-TR-83-083). Air Force Aerospace Medical Research Laboratory.	1983	Injury	HRV
Phillips, C. A., & Petrofsky, J. S. (1983). Quantitative electromyography: Response of the neck muscles to conventional helmet loading. *Aviation, Space, and Environmental Medicine, 54*(5), 452–457.	1983	Performance	HRV
Seemann, M. R., & Lustick, L. S. (1982). Combination of accelerometer and photographically derived kinematic variables defining three-dimensional rigid body motion. In *2nd International Symposium of Biomechanics Cinematography and High Speed Photography* (Vol. 291, pp. 133-141). SPIE.	1982	Injury	Mathematical model
Lustnik, L. S., Williamson, H. G., Seemann, M. R., & Bartholomew, J. M. (1982). *Problems of measurement in human analog research (Report No. 82RO12)*. Naval Biodynamics Laboratory.	1982	Sub-injury	HRV
Huston, R. L., & Sears, J. (1981). Effect of protective helmet mass on head/neck dynamics. *Journal of Biomechanical Engineering, 103*(1), 18–23.	1980	Injury	Computational model
Thomas, D. J., Ewing, C. L., Majewski, P. L., & Gilbert, N. S. (1980). Clinical medical effects of head and neck response during biodynamic stress experiments. In *Advisory Group for Aerospace Research and Development High-Speed, Low-Level Flight* (SEE N 80-29990 20-51).	1980	Sub-injury	HRV

Citation	Year published	Study focus	Data source
Majewski, P. L., Borgman, T. J., Thomas, D. J., & Ewing, C. L. (1979). Transient intraventricular conduction defects observed during experimental impact in human subjects. In *Advisory Group for Aerospace Research and Development Models and Analogues for the Evaluation of Human Biodynamic Response, Performance, and Protection* (SEE N 79-31901 22-52).	1979	Sub-injury	HRV
Ewing, C. L., Thomas, D. J., & Lustick, L. (1979). Multiaxis dynamic response of the human head and neck to impact acceleration. In *Advisory Group for Aerospace Research and Development Models and Analogues for the Evaluation of Human Biodynamic Response, Performance, and Protection* (SEE N 79-31901 22-52).	1979	Sub-injury	HRV
Ewing, L., Thomas, D. J., Lustick, L., Muzzy III, W. H., Willems, G. C., & Majewski, P. (1978). Effect of initial position on the human head and neck response to+ Y impact acceleration. *SAE Transactions*, 3151–3165.	1978	Sub-injury	HRV
Smith, D. E., & Anderson, W. R. (1978). Predictive model of dynamic response of the human head/neck system to-Gx impact acceleration. *Aviation, Space, and Environmental Medicine, 49*(1 Pt. 2), 224–233.	1978	Injury	Computational model
Ewing, C., Thomas, D., Majewski, P., Black, R., & Lustick, L. (1977). *Measurement of head, T1, and pelvic response to -Gx impact acceleration* (Report No. 770927). SAE International, Inc.	1977	Sub-injury	HRV
Ewing, C., Thomas, D., Lustik, L., Muzzy, W., Willems, G., & Majewski, P. (1977). *Dynamic response of the human head and neck to +Gy impact acceleration* (Report No. 770928). SAE International, Inc.	1977	Injury	HRV/NHP
Ewing, C. L., Thomas, D. J., Lustick, L., Muzzy, W. H., Willems, G., & Majewski, P. L. (1976). *The effect of duration, rate of onset, and peak sled acceleration on the dynamic response of the human head and neck* (Report No. 760800). SAE International, Inc.	1976	Sub-injury	HRV
Muzzy, W. H., & Lustick, L. (1976). *Comparison of kinematic parameters between hybrid II head and neck system with human volunteers for-Gx acceleration profiles* (Report No. 760801). SAE International, Inc.	1976	Injury	HRV/ATD
Ewing, C., Thomas, D., Lustick, L., Becker, E., Willems, G., & Muzzy, W. (1975). *The effect of the initial position of the head and neck on the dynamic response of the human head and neck to -Gx impact acceleration* (Report No. 751157). SAE International, Inc.	1975	Sub-injury	HRV
Ewing, C. L., & Thomas, D. J. (1973). *Torque versus angular displacement response of human head to-Gx impact acceleration* (Report No. 730976). SAE International, Inc.	1973	Sub-injury	HRV
Ewing, C. & Thomas, D. (1971). *Human dynamic response to -Gx impact acceleration* (Report No. AGARD-CP-88-71). Advisory Group for Aerospace Research and Development.	1971	Sub-injury	HRV
Ewing, C., Thomas, D., Patrick, L., Beeler, G. & Smith, M. (1969). *Living human dynamic response to —Gx impact acceleration II —Accelerations measured on the head and neck* (Report No. 690817). SAE International, Inc.	1969	Sub-injury	HRV
Alem, N. (n.d.). *Effects of head supported mass on helicopter aviator performance in simulated flight* [Unpublished manuscript].		Performance	HRV
Fraser, S. (n.d.). *UH-60 flight simulator performance while wearing various helmet configurations* [Unpublished manuscript].		Performance	HRV

Appendix B. Summary of USAARL, UVA, and NBDL Datasets

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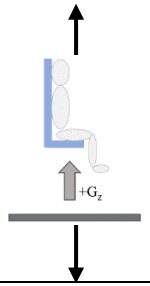
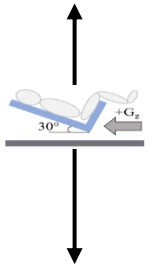
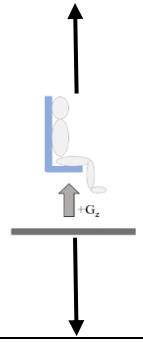
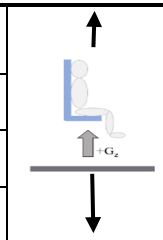
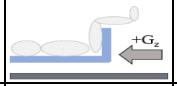
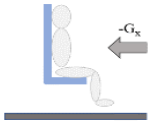
Table B1. Summary of USAARL, UVA, and NBDL Datasets*

Dataset	HRV/ PMHS	Head-supported mass		Number of runs	Accelerative exposure							Resulted in cervical spine injury
		Added mass (kg)	Description		Direction	Description	Peak G	Onset (G/s)	Duration (ms)	Change in velocity (ft/s)	Device of insult	
USAARL	PMHS	NA	No HSM	4	+Z		22	1300-1500	NA	42	VAT at USAARL	Yes
	PMHS	NA	No HSM	3	+Z		22	1300-1500	NA	42	VAT at USAARL	No
	PMHS	NA	No HSM	2	+Z		22	900-1200	NA	42	VAT at USAARL	No
	PMHS	NA	No HSM	1	+Z		16	900-1200	NA	42	VAT at USAARL	Yes
	PMHS	NA	No HSM	4	+Z		16	900-1200	NA	42	VAT at USAARL	No
	Total VAT Runs			**14**								
UVA	PMHS	2.0	2.0 kg at Head CG with Halo Device	1	+XZ		17	NA	NA	33	Horizontal accelerator	Yes
	PMHS	1.7	1.7 kg at Head CG with Halo Device	4	+XZ		15-31	NA	NA	30-43	Horizontal accelerator	Yes
	PMHS	NA	No HSM	1	+XZ		17	NA	NA	33	Horizontal accelerator	Yes
	Total UVA Runs			**6**								
NBDL	HRV	NA	Unhelmeted	1	+Z		3.13	59	305	18	VAT at NBDL	No
	HRV	1.25	Frame+ Skullcap	14	+Z		2.79-9.01	92-128	261-282	27-32	VAT at NBDL	No
	HRV	1.55	0.3 kg at eye level	17	+Z		2.92-9.06	117-185	235-264	32-40	VAT at NBDL	No
	HRV	1.85	0.6 kg at eye level	17	+Z		2.87-9.04	NA	NA	NA	VAT at NBDL	No
	HRV	1.55	0.3 kg at 45°	14	+Z		2.77-9.04	NA	NA	NA	VAT at NBDL	No
	HRV	1.85	0.6 kg at 45°	15	+Z		2.92-9.11	NA	NA	NA	VAT at NBDL	No

Dataset	HRV/ PMHS	Head-supported mass		Number of runs	Accelerative exposure							Resulted in cervical spine injury
		Added mass (kg)	Description		Direction	Description	Peak G	Onset (G/s)	Duration (ms)	Change in velocity (ft/s)	Device of insult	
NBDL	HRV	1.75	0.5 kg at Top of Head	13	+Z		2.94-9.16	NA	NA	NA	VAT at NBDL	No
	HRV	1.80	0.275 kg at 45° and 135°	16	+Z		3.03-9.00	NA	NA	NA	VAT at NBDL	No
	HRV	2.35	0.550 kg at 45° and 135°	19	+Z		2.94-9.12	NA	NA	NA	VAT at NBDL	No
	HRV	NA	No HSM	205	+Z		1.95-12.25	NA	NA	NA	VAT at NBDL	No
	HRV	NA	No HSM	380	+Z		2.0-12.25	NA	NA	NA	Horizontal accelerator at NBDL	No
	HRV	1.25	Frame+ Skullcap	37	-X		3. 00-9.14	53-227	220-312	18-43	VAT at NBDL	No
	HRV	NA	No HSM	1028	-X		1.95-15.91	148-1095	6-1040	13-38	Horizontal accelerator at NBDL	No
	Total NBDL Runs			**1776**								
	Total Runs			**1796**								

*CG = center of gravity; ft/s = feet per second; G = acceleration due to gravity; G/s = acceleration due to gravity per second; HRV = human research volunteer; HSM = head-supported mass; kg = kilogram; ms = millisecond; NA = not applicable; NBDL = Naval Biodynamics Laboratory; PMHS = post-mortem human surrogate; UVA = University of Virginia; USAARL = U.S. Army Aeromedical Research Laboratory; VAT = vertical acceleration tower

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