Injuries and Injury Risk Curves from Historical Non-human Primate Whole-body, +Gz Acceleration Tests

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Abstract To address acceleration injuries occurring in military environments, a unique series of non-human primate (NHP) experiments was conducted by the US DoD at the Naval Biodynamics Laboratory (NBDL). This analysis focused on corresponding injuries and injury risk curves for +Gz/vertical impact acceleration experiments. Data from 27 rhesus macaque whole-body axial acceleration tests were examined. Injury outcomes were determined using pre- and post-test data from subject records. Injury data were categorized according to affected region: thoracic, cervical, or cardiovascular. Each exposure was assessed as (1) non-injurious or (2) injurious, and peak sled accelerations were used to derive injury risk curves. Of the 27 accelerations, 11 were non-injurious and 16 were injurious. Aorta injuries and spine fractures were among the principal outcomes. Accelerations of 42 g and 55 g were associated with 25% and 50% probabilities, and the normalized confidence interval sizes (NCIS) were 0.40 and 0.84, respectively. Examinations of the kinematics in conjunction with the injuries revealed the mechanism of spinal injury to be flexion posture combined with the restraint loading the torso during vertical acceleration. These injuries parallel those encountered in automotive and military environments, offering insight into scaling NHP acceleration thresholds to human tolerances in future work.

Keywords Spine injury, Impact acceleration, Injury risk curves, Impact response, Vertical acceleration

I. INTRODUCTION

The United States Naval Biodynamics Laboratory (NBDL) initiated research efforts in the 1970's to determine human tolerance through non-contact impact acceleration runs [1]. This research spanned approximately twenty-five years until the NBDL testing facility was closed as part of the 1996 Base Realignment and Closure. Studies were conducted using physical and biological models, consisting of human research volunteers (HRVs), anthropomorphic test devices (ATDs), and Non-Human Primates (NHPs). Non-contact impact acceleration testing with NHP took place between 1973 and 1989, with a total of 400 NHP exposures logged by researchers. Non-contact impact acceleration is acceleration induced without direct contact to the test subject. Physiological and biomechanical data were gathered from the NHP before and during these runs, with pathological assessments conducted post-run. Sensor and photo data were collected using equipment and subject-mounted sensors and phototargets used in conjunction with high-speed film.

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Of the 400 exposures, 366 were performed using the horizontal accelerator (HA) and 34 were performed using the vertical accelerator (VA) [1]. The exposures covered a variety of vectors: front (-Gx), rear (+Gx), lateral (+/-Gy), axial/cranial-caudal (+Gz), and oblique (Gxy, Gxz). While the HRV exposures were non-injurious, the NHP exposures to impact accelerations included non-injurious and injurious runs. Of particular interest to the aviation community, and the focus of this analysis, is the set of injurious NHP +Gz experiments. Accelerative +Gz loading is experienced during aviation seat ejections, crashes, and underbody blasts.

In 2007, the extensive NBDL collection was recovered for archival and digitization at the US Army Aeromedical Research Laboratory (USAARL) within the Biodynamics Data Resource (BDR) in partnership with Naval Air Systems Command (NAVAIR). Of the conferences and publications through which NBDL presented its work, modern analysis techniques such as survival analysis and injury risk curves were not developed.

It is important to determine the injuries, injury mechanisms, and injury risk curves from impact biomechanical experiments to define human tolerance to injury. A comprehensive analysis will assist in the development of injury criteria, specification/promulgation of safety standards for different applications (automotive, military, sports, and aviation), biofidelity evaluations of existing ATDs, and development of future ATDs. Since human subjects cannot be subjected to injury producing exposures, other biological surrogate models are used, such as post-mortem human subjects (PMHS) and animals. While PMHS have been extensively used in impact biomechanics, they lack the physiological inputs/outputs, a feature present in the in vivo human. Animal models provide this factor. NHPs allow changes in behavior, limb use, paraplegia, physiological responses, cardiac arrest, and respiratory arrest to be observed during and after experimental exposures to acceleration. These can be important indicators of brain or spinal cord injury that PMHSs are unable to provide. Active muscles capable of tensing are unlike PMHS muscles and may provide different kinematic results. Although porcine models have been used to determine neck injury tolerance (e.g. Nij), NHPs are the closest animal models that mimic the human [2-4]. The objective of the present study is to analyze the NHP runs conducted in the +Gz direction and develop injury risk curves.

II. METHODS

Data Source

A total of 6,600 horizontal runs (1972-1994) and 1,184 vertical runs (1986-1995) were conducted during the non-contact impact acceleration program at the NBDL. The HA, on which the majority of acceleration research was done, was powered by a 0.30 m (12 in) diameter, nitrogen-pressurized HYGE^{TM} system. This propelled the sled and occupant along the track with a thrust capable of up to 1,001 kN (225,000 lbf). Deceleration following the controlled acceleration pulse was driven by friction at a rate of 2.13 m/s^2 (7 ft/s^2)to 3.96 m/s^2 (13 ft/s^2) over the 213.36 m (700 ft) enclosed track. Impacts were conducted in multiple directions including frontal, rear, lateral, off-axis, and axial. A nitrogen-powered HYGE^{TM} system supplied a controlled pulse to the VA carriage and occupant, propelling both upward along a 12.80 m (42 foot) vertical track with up to 177.9 kN (40,000 lbf) of thrust. Testing on the VA provided a more authentic +Gz loading experience than accelerations performed on the HA, which improved studies on ejection seat simulation [1].

The NHPs (106 rhesus macaque) were used as human surrogates for higher and potentially injurious accelerations, to which HRVs could not be safely exposed [1]. The use of NHPs as human testing surrogates is preferred, as they are the closest subject in terms of neuroanatomy and physiology to humans and are used in neuroscience [5]. All subjects used in this analysis were mature male adults undergoing between one and 21 total exposures, with two exposures per subject the most common. At least one exposure was conducted around 10 g to test the equipment and instrumentation before a run of a higher exposure took place. Each subject was seated and the torso restrained by either a rigid molded fiberglass shell restraint (Fig. 1) or a soft canvas restraint (Fig. 2) to isolate the head-neck complex. No head rest was used for either restraint system to allow for freedom of head and neck movement [1].

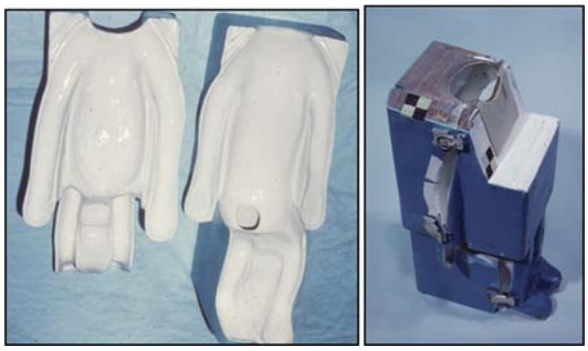

Fig. 1. Rigid restraint system custom molded for individual NHPs.

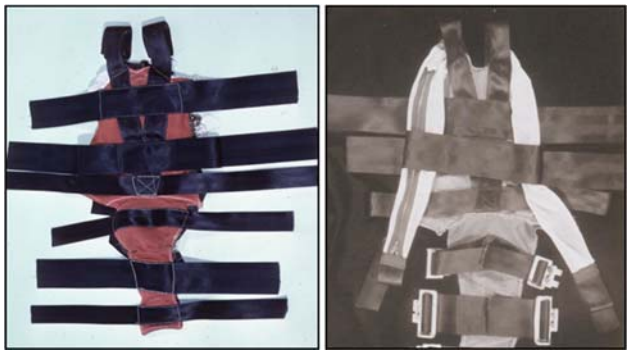

Fig. 2. Soft restraint system to be used for multiple NHPs.

Sensors and phototargets were mounted on the subjects and the sled. On-board cameras, usually providing a frontal view and often a lateral view, captured the kinematics at 1000 frames per second [6]. An A-plate with six accelerometers was mounted to the cranial pedestal on top of the head since size limitations of the macaques prevented head-neck kinematic collection by the same instrumentation used for the HRVs (Fig. 3). Electrophysiology data were collected before, during, and after the impact event to supplement the subject's kinematic data. Additionally, the NHP collection includes subject maintenance records, radiology, histology, pathology, and necropsy reports [1].

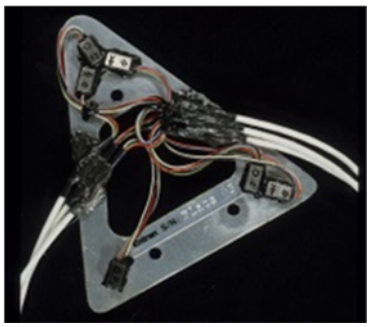

Fig. 3. A-plate with six accelerometers that were mounted to the cranial pedestal

Injury Assessment and Classification

All runs for this analysis were to have the acceleration impact applied to the sled/carriage in the +Gz direction on the horizontal or vertical accelerator. Only final runs at potentially injurious levels, 38 g's or higher, were considered. Of the 400 total rhesus macaque whole-body acceleration runs, 27 runs met the aforementioned criteria and are summarized in Table 1. Injury outcomes were defined according to the data accessible in the BDR from maintenance records and details from histology, radiology, pathology and necropsy reports [7]. Maintenance records contained a comprehensive log of NHP arrival date, medications provided, routine care or surgical procedures, lab work, and the subject's condition before and after experimental runs. Accounts of behavior, eating habits, and any changes from normal demeanor were recorded with the corresponding dates. These records were kept from the day of the NHP's arrival at the facility to the time of necropsy. Necropsy reports detailed the findings of the gross examination of the subject, any pathological diagnosis, and comments from the veterinarian on the NHP's conditions. This information, compiled from all of the available records, proved critical for identifying and discerning the source of injury following a run.

Table 1
Runs Qualifying for This Analysis

Species	Sex	Age Range	Weight Range (kg)	Number of Runs on Horizontal Accelerator	Number of Runs on Vertical Accelerator	Peak Sled Acceleration Range (g)
Rhesus – Macaca Mulatta	M	12-20+*	5.9-14.29	12	15	38.9-85.8

*Some ages are estimated or unknown.

A team consisting of a neurosurgeon, a research flight surgeon, a veterinarian, and biomedical and biomechanical engineers reviewed these records and high-speed films as tools to determine injury occurrence and mechanism of injury. A run was considered injurious when an injury directly resulted from the acceleration exposure. With this definition, restraint bruising was considered an injury since the soft tissue injury occurred as a direct result of the accelerative event. Injuries caused by instrumentation complications, such as demyelination resulting from electrode placement, were not included as an accelerative injury.

Injuries were categorized as cardiovascular, thoracic, or cervical. Cardiovascular injuries are defined as affecting tissue comprising the heart. Thoracic injuries consist of damage to the tissue within the thoracic region and first lumbar vertebrae, and include damage to the ribs, the spinal column from T1 to L1, all musculature, internal organs, and the epidermis (excluding the cardiovascular system). Cervical injuries are defined as any injury to the cervical spinal column or the surrounding cervical soft tissue.

Injury Risk Curve Analysis

The determination of the risk curves followed the methodology presented in Olszko's initial analysis of the +/-Gx impact direction [7]. Briefly, the peak sled acceleration, expressed as acceleration units, g, was used as the primary response variable to estimate the risk. Survival analysis was based on the recommendations of the International Standards Organization (ISO), modified by adding more quantitative metrics. Each exposure was assessed as (1) non-injurious or

(2) injurious and the g-value treated as a censored observation, where non-injurious exposures were treated as right-censored and injurious exposures treated as left-censored. The corrected Akaike Information Criterion (AICc) was used to select the optimal distribution for which the lognormal, log-logistic, and Weibull distributions were chosen. The mean acceleration-based risk curve, and curves corresponding to plus-minus 95% confidence intervals (CI) were obtained from the optimal distribution. The delta method was used to determine the CI [8]. The normalized CI size (NCIS) was defined as the ratio of the width of the CI to the magnitude of the g-value from the optimal model at a specific risk level. It is given by the following equation (where UL and LL represent the upper and lower limits of the CI and μ represents the mean value of the metric at the chosen risk level [9]).

$$NCIS_{risk\,\%} = \frac{(CI_{UL} - CI_{LL})_{risk\,\%}}{\mu_{risk\,\%}}$$

A lower NCIS magnitude is associated with a tighter confidence interval at the chosen probability level. Based on the NCIS magnitudes, the quality indices of the curves at specific risk levels were chosen. The index was defined as good, fair, marginal, and acceptable based on values of NCIS < 0.5, 0.5 ≤ NCIS < 1.0, and 1.0 ≤ NCIS ≤1.5, and NCIS > 1.5, respectively [9].

III. **RESULTS**

Of the 400 NHP impact exposures, 27 met the criteria for analysis. From these exposures there were 11 non-injurious and 16 injurious runs. Two of the runs, at 59.7 and 66.8 g, were immediately fatal. Concerning specific injuries, Aorta hemorrhaging and thoracic spinal fractures with hemorrhaging in the muscles surrounding the fractures were among the principal outcomes. Hemorrhaging within the heart, lungs, spleen, kidneys, and adrenals was noted in the necropsy reports. Cervical injuries were manifested as cervical muscle hemorrhages. Spinal cord damage was reported in two cases at the levels of thoracic spinal fracture. Injury specifics are included in Table 1. Injury occurrences by category are: 16 thoracic, 7 cardiovascular, and 4 cervical. Thoracic injuries occurred above 39.5 g, while cardiovascular and cervical injuries occurred above 50.7 and 69.5 g, respectively.

Table 1: Individual Injuries

ID	Neural		Osteoligamentous structures		Organ		Muscle injury		Other injury	
	Description	Severity	Description	Severity	Description	Severity	Description	Severity	Description	Severity
1	Epidural hemorrhage, T3-9	Minor	T6-7 lamina fracture	Minor			Intercostal muscles T4-8	Minor		
2	Epidural, subdural cord hemorrhage, T2-9	Severe	T5-6 spine ligaments	Severe	Hemorrhage lung	Severe	Ventral cervical muscles	Severe		
			T6 left lateral arch	Severe	Hemorrhage kidney (left)	Severe	Intercostal muscle T5-6	Severe		
					Hematoma spleen	Moderate	Occipital muscle	Minor		
					Dorsal tongue	Minor	Dorsal spinal muscles T5-T6	Severe		
					Trachea	Severe				
3					Liver	Severe	Diaphragm	Severe		
					Pancreas	Mild	Dorsal spinal muscles, T4-6	Mild		
4	Epidural hemorrhage, T8-9	Moderate	Compression fracture with luxation T8-9	Severe						
	Subdural hemorrhage, T8-10	Moderate			Heart	Severe	Muscles of the shoulder and chest	Minor		
	Cord hemorrhage, T3-10	Severe			Lung	Severe	Intercostal muscle T4-12	Moderate		
					Adrenal	Mild	Ventral vertebral T4-12	Moderate		

ID	Neural			Osteoligamentous structures			Organ		Muscle injury			Other injury		
							Stomach	Moderate						
5									Shoulder	Mild	subcuatenous T5-10			Moderate
6	Subarachnoid hemorrhage	Mild		Compression fracture with luxation T5-7	Severe		Lung	Severe	Intercostal muscle T3-8	Severe				
							Aorta	Severe	Diaphragm	Mild				
7	Subarachnoid hemorrhage	Mild		Compression fracture T8	Mild		Aorta	Moderate	Intercostal muscle T4-7	Moderate				
				Spinous processes fracture T6-7	Moderate				Ventral vertebral T4-12					
8									Intercostal muscle T6-10	Moderate				
9							Kidney	Mild	Intercostal muscle T2-12	Mild				
10							Lung	Severe	Dorsal vertebral T5-8	Mild				
							Esophagus	Moderate						
11	Epidural, T1-10	Mild		Compression fracture T7-8	Moderate		Esophagus	Severe	Intercostal muscle T1-12					
	Subarachnoid hemorrhage	Mild					Aorta	Moderate	Ventral vertebral T1-12					
12									Intercostal muscle T8-11		subcuatenous shoulder	Mild		

ID	Neural		Osteoligamentous structures		Organ		Muscle injury	Other injury	
							Ventral vertebral T8-11		
13					Adrenal	Mild		subcuatenous shoulder	Mild
					Aorta	Mild		subcuatenous C7-T8	Mild
14					Heart	Mild	Ventral muscles T10-11		
15	Cord at T5-6	Moderate	Compression fracture T6		Adrenal	Mild	Dorsal vertebral T5-8	subcuatenous T5-8	Moderate
							Intercostal muscle T3-8		
16	Cord at L1-4	Moderate	Compression fracture L1	Moderate	Spleen	Mild	Dorsal vertebral T12-L4	Severe	
					Aorta	Moderate	Intercostal muscle T4-12	Severe	
					Heart	Mild			

Based on the AICc for the three distributions, the Weibull distribution was found to be the most optimal function and parametric analysis was deemed appropriate. The mean injury risk curve and the associated plus-minus 95% CI curves are shown in Fig. 4. The mean acceleration magnitudes of 42 g and 55 g were associated with 25% and 50% probabilities. Specific magnitudes at other risk levels are shown (Fig. 5). The NCIS corresponding to these mean magnitudes were 0.40 and 0.84, respectively. Table 2 includes the NCIS magnitudes at different injury risk levels. Fig. 6 shows the NCIS data at different injury risk levels. The quality indices were assessed to range from the good to the acceptable range (Table 2).

Table 2: Summary of data

Risk Level	95% Confidence interval (g)		Mean acceleration (g)	NCIS	Quality index
	Lower bound	Upper bound			
0.05	10	61	25	2.06	Acceptable
0.10	16	62	31	1.50	Marginal
0.25	28	64	42	0.84	Fair
0.50	45	68	55	0.40	Good
0.75	57	83	69	0.38	Good
0.90	60	108	80	0.60	Fair
0.95	61	125	87	0.74	Fair

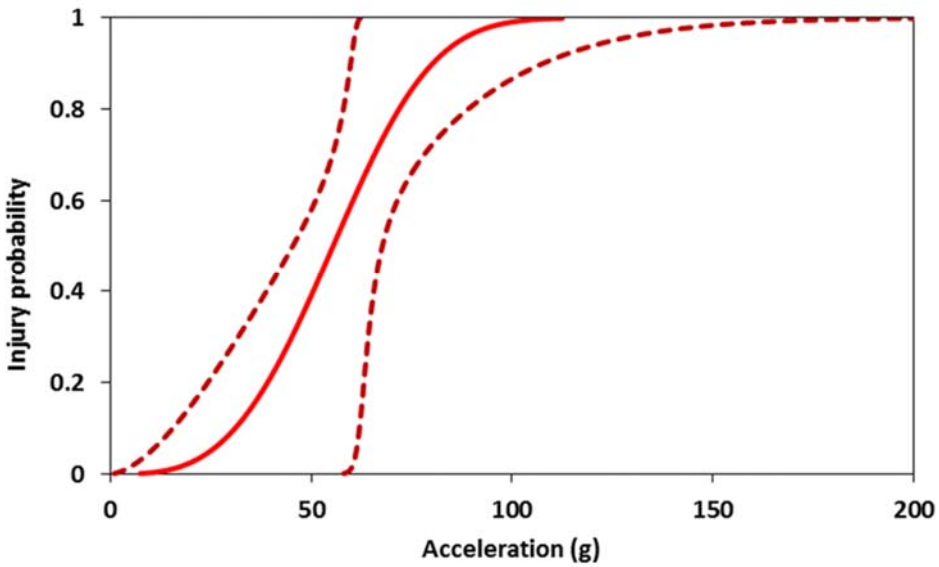

Fig. 4. Injury risk curve for vertical loading. Solid curve represents the mean response, and the dashed curves represent the plus-minus 95% confidence intervals.

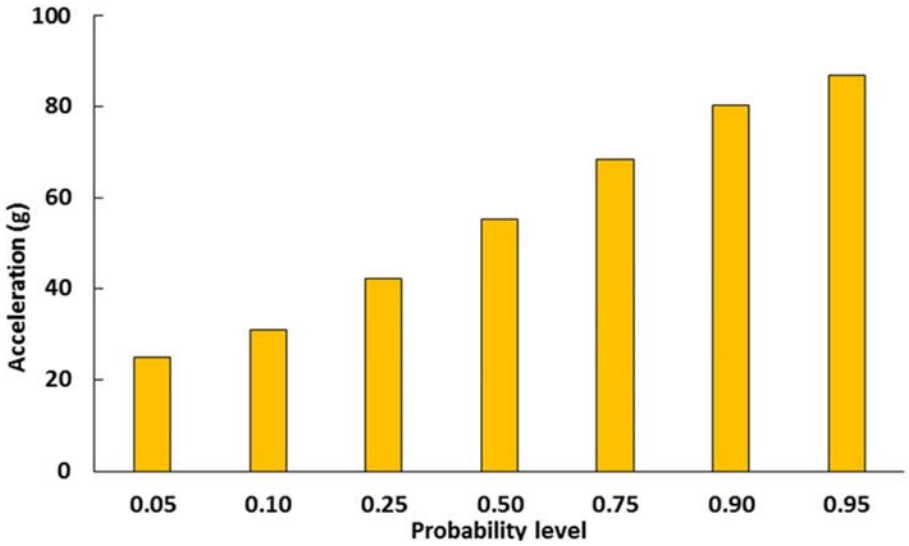

Fig. 5. The magnitudes of the acceleration at different risk levels.

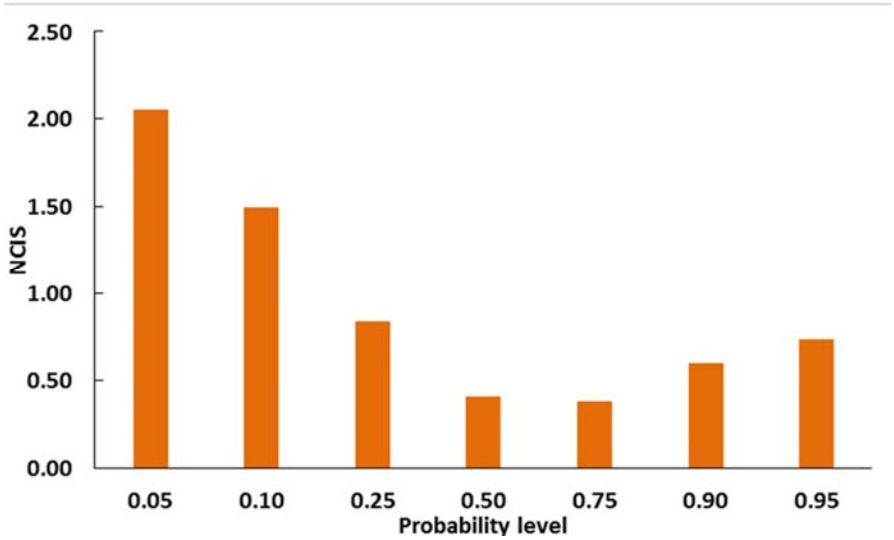

Fig. 6. The normalized confidence interval sizes (NCIS) at different risk levels.

IV. DISCUSSION

The most common injuries observed in the thoracic region were spinal fractures accompanied by hemorrhaging. Of particular interest were the occurrences of compression fracture, crush fracture, and other vertebral fractures that have been observed in events applying compressive loading to the spine [10-12]. Organs within the thoracic cavity, the epidermis beneath the restraints, and the musculature

surrounding the thoracolumbar spinal column exhibited hemorrhaging. Cervical injuries sustained were hemorrhage of the muscle surrounding the cervical spine and one case of minute cervical cord lesion. The mechanism of these injuries was thought to be attributed primarily to compressive loading while the neck is in flexion and the restraint is loading the torso during the vertical acceleration. Movement of the neck into flexion position during the initial period of acceleration was confirmed using the high-speed film of the individual runs. Injuries similar to those observed from this dataset are prevalent in military events where crewmembers are exposed to vertical acceleration [11, 12] and those observed in automotive crashes [13, 14]. In the military environment, military personnel are subjected to adverse events such as parachute opening shock, aircraft ejections, underbody blasts, and crash landings exposing aviators to 10 to over 200 g's along the vertical axis of their spines [15, 16, 17]. Impact accelerations like those mentioned have resulted in compression fractures, subdural hemorrhages, cervical spine fractures and strains, thoracic organ damage, and difficulty breathing in aviators [18]. When comparing the exposures experienced in military environments to those seen by the NHPs, the exposures were well within the acceleration ranges that are experienced by military personnel during underbody blasts and crash landings. Injuries similar to those sustained by military personnel during +Gz acceleration were sustained by the NHPs in the impact acceleration program. Compression fractures, organ damage, difficulty breathing, and cervical fracture or strain were noted among the NHP injuries, showing that NHP injuries are relevant to human injuries for +Gz impact acceleration. Scaling of the acceleration levels between the two models, NHP and humans, is an important topic the authors intend to pursue in future work. It has been suggested that cervical damage doubles the risk of thoracolumbar fracture in motor vehicle crashes [19], making the injuries sustained during flexion of greater concern for the remaining regions of the vertebral column. Among the analyzed NHP dataset, 3 of the 4 runs resulting in cervical region damage also had an incidence of fracture in the thoracolumbar spine. Both fatalities were attributed to significant bone and organ trauma, specifically to the hearth and aorta.

The minimum accelerations at which thoracic, cardiovascular, and cervical injury occurred were 39.5 g, 50.7 g, and 69.5 g, respectively. Upon analysis, a 50% risk threshold at 55 g was found among the +Gz NHP dataset. While it has been reported that accelerations above 110 g during a frontal acceleration are acutely fatal and the threshold for injury is between 105 g and 110 g [20], there were two fatal runs (59.7 g and 66.8 g) noted in this dataset. The same cited study suggested that tissue damage can occur as low as 78 g for frontal impact, and at or above 97 g for rear impact, although no injury risk curves were developed [20]. The change in loading direction, axial rather than frontal or rear, is likely to be the cause of the lower g threshold associated with tissue damage and fatal exposures in this analysis.

One limitation to this analysis was the use of records written between 1973 and 1989 to determine injury occurrence. Relying solely upon the reports available meant that not only was the knowledge of injuries limited to what was observed and recorded at that time, but also the research techniques since then have improved. While the records detailed findings pre- and post-run, it is possible that some relevant form of injury was missed at the time of examination. Further limitations were, rather than including rotational or individual kinematic data, peak sled acceleration was the focus of this study. The effects of anesthesia, initial head position, and duration of the acceleration were not considered.

Data will be made available to the research community through the BDR relational database, after which it will be possible for the research community to pursue other types of analyses. With this dataset, comparisons between loading applied in the horizontal and vertical direction using nearly-identical setups would provide insight into orientation effects that may otherwise be overlooked in biomechanical test development and analysis. Future assessment can incorporate initial head position, range of onset rates and duration, use of anesthesia, and other run variables not considered in this initial analysis. Also, a look into the histology can provide insight into tissue injuries that can be observed using staining and imaging techniques that were unavailable at the time of the NBDL experiments. Such analyses provide opportunities to scale NHP data for human application as well as open the possibility to make comparisons between all three subject types represented in the NBDL collection: NHP, ATD, and HRV. These comparisons, supplemented by future PMHS tests, will provide a robust and controlled dataset useful for validating and improving existing safety criteria. As autonomous vehicles are gaining prominence and mission essential equipment (e.g., personal protective equipment, seating systems) are undergoing evaluations in the military, using this dataset is vital for understanding injury mechanisms and mitigating future injury.

V. CONCLUSIONS

This study analyzed injury data and accelerations from 27 whole-body NHP non-contact impact acceleration experiments conducted by the US Military in the +Gz direction. Injuries to different body regions were extracted from the NHP records collected pre- and post-run by NBDL researchers. These exposures and injuries parallel those from military events (e.g., helicopter crash, aviator ejection), offering insight into potential injury mitigation techniques/technologies. The peak sled accelerations from the NHP runs were used to develop injury risk curves using survival analysis techniques. Aorta injuries and spine fractures were the principal outcomes among the injuries observed. Accelerations of 42 g and 55 g were associated with 25% and 50% probabilities, and the NCIS were 0.40 and 0.84, respectively. With the use of appropriate scaling techniques, these acceleration thresholds will be comparable to human tolerances under +Gz loading.

VI. ACKNOWLEDGEMENTS

This study was supported by Defense Health Program funding from the Office of the Assistant Secretary of Defense for Health Affairs (DHA) through the U.S. Army Medical Research and Materiel Command (USAMRMC) Broad Agency Announcement under the Joint Program Committees (JPC-5 and JPC-6), W81XWH-16-1-0010, and the resources and use of facilities at the Zablocki VA Medical Center, Milwaukee, Wisconsin. Any views expressed in this paper are those of the authors and are not necessarily representative of the funding organizations.

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