Neck Injury Criteria Formulation and Injury Risk Curves for the Ejection Environment: A Pilot Study

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Background: Helmet mounted displays provide increased pilot capability, but can also increase the risk of injury during ejection. The National Highway Transportation Safety Administration's (NHTSA's) neck injury criteria (N_{ij}) metric is evaluated for understanding the impact of helmet mass on the risk of injury and modified risk curves are developed which are compatible with the needs of the aviation community. ***Methods:*** Existent human subject data collected under various accelerative and head loading conditions were applied to understand the sensitivity of the N_{ij} construct to changes in acceleration and helmet mass, as well as its stability with respect to gender, body mass, neck circumference, and sitting height. A portion of this data was combined with data from an earlier postmortem human subject study to create pilot study modified risk curves. These curves were compared and contrasted with the NHTSA risk curves. ***Results:*** A statistically significant difference in the peak mean N_{ij} was observed when seat acceleration increased by 2 G, but not when helmet mass was varied from 1.6 kg to 2 kg at a constant seat acceleration of 8 G. Although NHTSA risk curves predict a 13% risk of AIS 2+ injury for the 8-G, 2-kg helmet condition mean N_{ij} of 0.138, no AIS 2+ injuries were observed. Modified risk curves were produced which predict a 0.91% risk of AIS 2+ injury under these conditions. ***Discussion:*** The N_{ij} was shown to be sensitive to changes in acceleration and generally robust to anthropometric differences between individuals. Modified risk curves are proposed which improve risk prediction at lower N_{ij} values.

Keywords: HMD, pilot, aviation safety, risk curves.

HELMET MOUNTED displays (HMDs) are becoming human-machine interface equipment in manned flight. They have been shown to increase the performance of operators in their weapon systems and thus increase overall mission effectiveness by adding capabilities such as enhanced night vision and information fusion, which have the potential to enhance mission effectiveness across the spectrum of military operations (24). Unfortunately, this increased capability is often accompanied by increased mass, which can threaten pilot safety during ejection (19,21,26) and contribute to chronic neck and back injuries (9,20). Of particular interest, the increased mass has the potential to increase the risk of operator neck injury if the pilot is subjected to accelerative environments like ejection. Injury due to a heavier HMD in this environment could range from low severity strains and muscle tears to high severity cervical spine fractures and ligament ruptures (4,26). Pilot anthropometric factors may also affect the likelihood of injury from neck loads induced by head-born mass, and recent changes in DOD manning requirements have increased the diversity of anthropometric characteristics among pilots (16). Therefore, it is important that pilot neck response be understood and characterized using a standard evaluation criteria that considers the influence of pilot anthropometric and biomechanical characteristics.

The National Highway Transportation Safety Administration (NHTSA) has established a frontal impact neck injury criteria (N_{ij}) for assessing risk of severe injury in automotive crashes (12,13). This criteria provides a quantitative method for evaluating and differentiating automotive crash and restraint systems where the quantitative metric can be related to the likelihood of injury in specified severity categories. This metric has a strong foundation in biomechanics and relies upon results of crash tests with standardized Hybrid-III Anthropomorphic Test Devices (ATDs) to provide criteria for predicting the likelihood of injury to persons with varying anthropometric characteristics (12). The ability to define a relationship between the performance of the automotive crash and restraint system and the likelihood of injury is a key attribute of the N_{ij} criteria, which does not exist for any known HMD or escape system evaluation method.

This research seeks to understand the applicability of the N_{ij} formulation, or a more comprehensive criterion having similar characteristics, to the evaluation of helmet systems of varying mass in an accelerative aviation environment. Specifically, this research employed archived, Air Force (AF) frontal impact ($-G_x$) data (11) to address the following questions:

1) Is the N_{ij} formulation sensitive to changes in acceleration and helmet mass?
2) Is the N_{ij} formulation sensitive to variation in anthropometric characteristics, including gender, body mass, neck circumference, and sitting height for subjects who are exposed to variations in acceleration and helmet mass?
3) Are the NHTSA neck injury risk curves applicable to the aviation accelerative environment and, if not, what is an appropriate family of risk curves?

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NHTSA's neck injury criteria, the N_{ij}, established critical limits in four types of neck loading which are dominant in frontal impact automotive crashes involving accelerative forces primarily in the $-G_x$ axis. This criteria includes axial loading (F_Z, tension, and compression) and sagittal plane bending moments (M_Y, flexion forward, and extension rearward) using a methodology initially presented by Klinich et al. (18). Development of this injury criterion included applying previous biomechanical neck load and resultant injury research involving volunteer humans, porcine subjects, and postmortem human subjects (PMHS). This same research established critical limits for these four load pathways (12). The formula used to calculate the N_{ij} is:

$$N_{ij} = \frac{F_Z}{F_{Z\text{int}}} + \frac{M_Y}{M_{Y\text{int}}}$$

In this equation, F_Z and M_Y are specifically observed instantaneous peak upper neck loads in a test automotive crash with the appropriately sized Hybrid-III ATD (i.e., small-sized female, mid-sized male, and large-sized male) designed to evaluate the performance of a restraint system. The values of F_Z and M_Y are the simultaneous instantaneous peak values that result in the largest N_{ij} over the time history of the test. The values F_{Zint} and M_{Yint} are critical load values established by NHTSA for the maximum axial load in tension or compression and the measured flexion/extension bending moment established for various occupant size ATDs (12). The critical load values (also called intercept values) perform two important functions in the criteria. First, they assign relative importance to each mode of loading in the combined-force N_{ij} equation based upon observed biomechanical properties of the neck relative to injurious pathways (e.g., they normalize the axial load and the bending moments based upon the likelihood of these individual components to induce injury). Second, they allow the criteria to be normalized to occupant size as well as to a desired numerical value for ease of use. As such, anthropometric differences are accounted for within the criteria.

Injury risk curves allow decision makers to design systems to a specific level of acceptable risk and serve as the foundation of any injury criterion (23). These curves are formed using various statistical techniques, most commonly logistic regression or survival analysis, modeling injury probability as a function of some input, in the current case neck loading in the form of the N_{ij} (2,10). These models define the risk of injury based upon statistical analysis of experimental data with specific force input, or combination of forces, resulting in a binary outcome (injury/no injury) as the dependent variable specified at a certain defined injury level. Risk curves were generated for the NHTSA N_{ij} based upon a logistic regression of paired porcine injury and ATD neck load data which were scaled to develop limits for acceptable risk of injury to human occupants (12). Specific injury level for each curve is based on Abbreviated Injury Scale (AIS) classification (1). Based upon the consensus that no more than a 22% risk of AIS 3 or greater neck injury was acceptable, NHTSA applied the AIS 3 curve to select $N_{ij} = 1.0$ as the performance limit (12). Similar risk curves were constructed from the data for AIS 2, 4, 5, and 6 injuries. Within the automotive application, a test that produces Hybrid-III ATD neck loads that exceed a N_{ij} value of 1.0 fails the criteria.

When a pilot ejects from an aircraft he or she is subjected to four different phases, each phase exposing the pilot to different forces. In order, these phases are: catapult stroke, windblast, seat stabilization, and parachute opening shock. Most aviation-specific ejection studies have focused on the effects of the first phase, catapult stroke, in which the accelerative forces presented by the ejection mechanism act upon the head and neck in the positive z axis (upward, or $+G_z$). However, the accelerative forces during all phases of ejection are a concern with increased helmet mass. These additional phases can result in accelerative forces acting in the other major planes, $-G_x$ and G_y, respectively. An aviation specific neck injury criterion may need to consider each of these forces. The current study focuses on forces in the $-G_x$ plane, consistent with the windblast phase of the ejection sequence, as this phase can provide forces similar to those experienced during frontal impact and permits the application of the NHTSA N_{ij} neck formula to existing human data. Research within the aircraft community has demonstrated that compressive and shear neck load, as well as neck bending moments, typically increased linearly with increases in acceleration and helmet mass (4). Further studies have investigated the effect of helmet mass in accelerative environments within the other major axes (G_x and G_y) and compared male and female subjects in impact tests to expand the field of knowledge relevant to the smaller individuals and to ensure this population was not put at undue risk as a result of heavier HMDs (3,5,6). Although early studies recommended that total helmet mass should be kept under 2 kg to prevent injury to pilots (4), a more comprehensive criterion, analogous to the N_{ij}, has not been developed within the aviation community.

The use of the N_{ij} has been proposed as part of an overall neck injury criteria to evaluate aircraft escape system safety using ATDs as human surrogates (22,23). However, to the authors' knowledge, this criterion has not been evaluated, qualified, or verified using human neck response data as an evaluative tool for HMD and escape system design. Within this application a N_{ij} performance limit of 0.5, which corresponds with a 9.6% risk of AIS 3 or greater, has been proposed rather than NHTSA's 1.0 limit (1,22). The lower performance limit was selected because a military pilot must be capable of avoiding capture or navigating to an extraction point after ejection, while NHTSA requires that a passenger survive an accident under the assumption that first responders will arrive on site to attend to any injuries. The escape system oversight office of the Air Force Life Cycle Management Center (AFLCMC) has clarified the requirement for AF aviation, specifying that a neck injury criteria be developed to evaluate HMDs and new escape systems such that acceptable injury rate should be 5% at an AIS 2 (moderate injury) (White JE. Personal communication; May 2012). In addition to the need for a comprehensive criterion, further development of the injury risk curves to meet AFLCMC requirements is also required.

METHODS

Data from a previously performed human subject experiment on the effects of variable helmet mass on neck response to $-G_x$ acceleration (11), which might represent the acceleration sustained from a frontal automotive impact or parachute opening phase of ejection, was used to understand the effects of interest on N_{ij} response. The test "HMD" was a standard AF flight helmet (HGU-55/P) modified to allow variable mass to be attached to the helmet, which was properly fitted and attached to the subject's head using standard chin straps. For ease of reference this test helmet will subsequently be referred to as the HMD.

Subjects

Data from three experimental test configurations were used in this analysis. In the first, 26 human subjects wearing a 2-kg HMD were subjected to 6 G of accelerative force. In the second, 24 subjects wore a 1.6-kg HMD and were subjected to 8 G, and in the third, 23 subjects wore a 2-kg HMD and were exposed to 8 G. Detailed information for the specific subjects participating in each of the tests is shown in **Table I**.

Procedures

During the test, volunteer subjects were seated vertically and restrained in a standard AF fighter aircraft ACES-II ejection seat. Subjects were instructed to "brace." Bracing is a technique taught in pilot training to use the neck muscles to force the head back into the head rest, as it is believed this action reduces neck injuries due to forward flexion. The seat was mounted to the test sled and subjects were accelerated rearward on the sled track at the specified acceleration level to measure the $-G_x$ neck responses. A triaxial linear accelerometer and an angular accelerometer mounted on a bite bar measured the head accelerations (11). The accelerative portion of the experiment lasted for about 200 ms. All of the tests were non-injurious, but neck stiffness or soreness (classified as less than AIS 1 injuries) was reported in approximately 15% of the tests, mostly at the higher helmet mass and acceleration levels (11). This post-test reporting was used by medical observers to determine subject safety and there were no clinical outcomes. All subjects had radiological scans taken before admittance to the subject panel and were cleared of any musculoskeletal and other pathological issues (e.g., observations of degenerative disks or osteoporosis) that would preclude them from participation in the study. Upon exit from the study panel, subjects typically underwent a brief survey performed by the medical examiner to check for pain or discomfort caused by the testing. If warranted, follow-on radiological

TABLE I. HUMAN SUBJECT ANTHROPOMETRY AND PEAK INSTANTANEOUS UPPER NECK LOADS.

							Test Conditions								
	Subject Anthropometry						8 G, 2-kg HMD			8 G, 1.6-kg HMD			6 G, 2-kg HMD		
	Body Mass (kg)	Gender	Height (cm)	Sitting Height (cm)	Age	Neck Circumference	M_Y (N-m)	F_Z (N)	N_{ij}	M_Y (N-m)	F_Z (N)	N_{ij}	M_Y (N-m)	F_Z (N)	N_{ij}
	54.9	F	154.9	81.9	20	32.5	-	-	-	34.4	182.7	0.26	24.8	2.7	0.16
	60.8	F	158.8	84.3	29	31.2	46.6	152.7	0.17	24.8	153.0	0.10	15.4	115.2	0.07
	65.3	F	160.0	88.3	28	32.9	44.6	192.0	0.17	43.6	321.6	0.19	23.9	61.5	0.09
	65.8	F	175.3	91.4	19	31.5	32.8	230.3	0.14	32.6	203.7	0.14	48.4	41.9	0.16
	66.2	M	172.7	91.4	24	36.9	-	-	-	27.1	240.1	0.12	19.5	45.7	0.07
	68.0	F	165.1	84.5	27	33.0	-	-	-	40.6	15.4	0.13	25.2	188.4	0.11
	69.9	F	165.1	88.3	46	31.9	32.9	126.3	0.12	39.3	470.7	0.20	28.0	32.0	0.10
	72.6	F	170.2	88.9	23	35.8	40.5	111.2	0.15	34.7	122.8	0.13	24.8	12.6	0.08
	73.5	F	167.6	87.6	28	33.1	395	379.1	0.18	31.2	183.6	0.13	-	-	-
	73.5	M	180.3	94.0	35	36.7	-	-	-	-	-	-	18.1	3.0	0.06
	73.9	F	175.3	95.3	25	32.2	19.9	103.5	0.08	23.5	103.0	0.09	-	-	-
	73.9	M	188.0	100.3	30	35.5	30.0	12.3	0.10	-	-	-	22.9	3.3	0.07
	77.1	M	177.8	88.9	24	35.2	33.4	221.8	0.14	28.6	7.9	0.19	-	-	-
	78.5	M	177.8	96.5	27	38.3	30.3	2.3	0.10	32.7	1.5	0.11	-	-	-
	78.5	M	180.3	95.3	36	38.1	40.3	170.4	0.16	28.8	77.6	0.10	27.8	13.0	0.09
	81.6	M	175.3	87.6	30	37.9	33.8	141.1	0.13	28.2	333.4	0.14	25.2	38.2	0.09
	81.6	F	157.5	87.0	23	36.8	38.4	18.4	0.13	52.6	202.1	0.20	29.2	13.8	0.10
	83.0	F	172.7	90.2	29	35.9	41.8	89.4	0.15	25.8	6.1	0.08	22.5	4.8	0.07
	83.0	M	185.4	97.2	28	38.2	35.8	430.6	0.18	-	-	-	-	-	-
	84.8	M	180.3	94.0	31	39.2	28.9	393.0	0.15	35.2	238.3	0.15	-	-	-
	88.5	M	182.9	96.5	27	38.8	31.5	129.5	0.12	39.6	4.5	0.13	23.3	11.4	0.08
	89.8	M	185.4	95.3	22	36.8	-	-	-	-	-	-	36.2	23.9	0.12
	90.7	M	181.6	96.5	37	39.7	37.0	429.8	0.18	34.0	3.2	0.11	26.6	88.3	0.10
	90.7	M	182.9	96.5	36	39.8	35.5	3.8	0.09	39.9	9.1	0.10	-	-	-
	99.8	M	189.2	99.1	33	39.8	48.8	228.8	0.15	28.5	449.4	0.12	-	-	-
	119.7	M	185.4	97.8	36	45.3	42.3	0.1	0.10	39.4	1.6	0.10	-	-	-
	126.1	M	193.0	97.8	32	45.0	64.6	10.1	0.16	41.8	72.4	0.11	28.1	7.1	0.07
Mean	80.4	N/A	175.6	92.3	29.1	36.6	37.7	162.6	0.14	34.2	148.0	0.14	26.1	39.3	0.09

scans were performed. If not, the subjects were released. These actions could be after several test series and were not indicative of any particular test, but detailed the effects of many tests that possibly could result from years of exposures.

In this experimental paradigm, the expected kinematic response is for the head to flex forward at some point during the frontal impact and then transition into combined tension and flexion. Thus only peak N_{TF} (neck tension/flexion) values were used when analyzing and making comparisons between each different experimental set up. Any other observed head and neck loading, like high compression values or other unexpected spikes in the N_{ij} values near the end of the test were considered artifacts of the test attributed to the decelerating sled and thus not used in the analysis. In the lower acceleration test (6 G) some subjects were able to maintain a sufficient brace through the impact to prevent forward flexion. Neck load data for these subjects showed their necks never experienced the expected tension-flexion combination and thus their data was not applied in this analysis.

Independent variables for this research included helmet mass and acceleration, as well as individual anthropometric parameters of the subjects. The dependent variables were resultant head, neck, and body accelerations, which were used to compute the neck loads used in the N_{ij} criteria (tension, compression, flexion, and extension). Neck and head mass was calculated using anthropometric measurements from each subject combined with separate regression equations from the literature for male and female neck volume and neck density values (15). Human subject neck loads were computed using subject anthropometry, exact helmet inertial properties, and bite bar recorded head accelerations at millisecond increments using a program employed in previous studies (11,15). This program is accurate for predicting forces during times of noncontact; thus, the initial portion of the test when the subject is bracing is not accurate, but these values were not used in this analysis since the peak loads occurred during peak acceleration of the head. At peak acceleration the head is off the headrest and not in contact with any other structures, so it becomes purely an inertial calculation. The program does not consider the internal motion of brain tissue and other soft fluids, but assumes the head behaves as a rigid body. While it is understood these calculated force values from acceleration vectors are not exact, they are of adequate accuracy for the purposes of further understanding human neck response to acceleration. N_{ij} values were subjected to statistical analysis to determine the sensitivity of N_{ij} to changes in acceleration and helmet mass as well as changes in anthropometric characteristics of the participants.

These same data were also applied to generate alternative AIS 2 and 3 human risk curves that are more appropriate for military aviation. In this portion of the analysis, the N_{ij} data from these three human subject test conditions (N = 67) were combined with a set of injurious PMHS N_{ij} data (N = 6) and risk curves were produced using a survival analysis. The six whole specimen PMHS data points were taken from previous research published by Cheng et al. (8). This data set provides the largest published, whole specimen, frontal impact research available which included both observed neck loads and injury level. Since this research was focused on injury risk curves generated from human and PMHS data, no data from matched paired PMHS/Hybrid-III tests were used. Frontal impact acceleration levels in this experiment were between 32 and 39 G. Peak observed neck loads were estimated using acceleration and head mass to calculate forces. Injury caused by the impact was determined by autopsy and specified on the AIS scale. Of the six PMHS, four experienced injuries classified as AIS 2 or greater and three experienced injuries classified as AIS 3 or greater (8). Thus the risk curve generated for AIS 2 injury and the risk curve generated for AIS 3 injury differ by a single injurious data point.

The N_{ij} values used for the regression for the human subjects were the peak instantaneous value of the combined axial and bending loads. Unfortunately no time history was published for the PMHS data. Thus, only the peak individual values were reported and applied for axial and bending loads. Note that these forces did not necessarily occur at the same time. Because of this, the injurious N_{ij} values are potentially higher than the peak instantaneous values specified by the NHTSA N_{ij} construct. Thus the resultant risk curve is slightly biased toward higher N_{ij} values. The N_{ij} values were calculated using the published NHTSA N_{ij} intercept values (13) based upon occupant size by applying the small-sized female intercept for subjects with body mass less than 63.5 kg, the mid-sized male intercept values for subjects with body mass between 63.5 kg and 90 kg, and the large male intercept values for subjects with body mass greater than 90 kg.

Statistical Analysis

Risk curves were generated through parametric survival analysis (17) following the methods used in research by Bass et al. (2). Survival analysis has recently been proposed as the standard in the biomechanics field for generating injury risk curves over the traditional logistic regression approaches which were used to generate the original risk curves associated with N_{ij} due to the ability of survival analysis to handle censored data (10). Using inverse prediction, the NHTSA and human data generated N_{ij} risk curves were compared at the 5% and 22% risk levels. As noted earlier, the 5% risk level is significant to military aviation and the 22% risk level is significant to the NHTSA application of the N_{ij} risk criteria.

RESULTS

To assess the sensitivity of N_{ij} to acceleration and helmet mass, the distributions of the N_{ij} values for each test case were analyzed. Data from the three tests were moderately skewed, thus nonparametric statistical methods were applied. Additionally, since each test case used overlapping pools of subjects, the samples were not independent and thus the related-samples Wilcoxon signed rank test was applied to compare N_{ij} values across the three acceleration and HMD mass values as well as within each test case between various groups of individuals. A statistically significant difference in the N_{ij} was observed when the acceleration was increased from 6 G to 8 G while the HMD mass of 2 kg was held constant (related-samples Wilcoxon signed rank test $P = 0.002$, $\alpha = 0.05$, mean N_{ij} of 0.0931 at 6 G and 0.138 at 8 G). When acceleration was held constant at 8 G and the HMD mass was varied from 1.6 kg to 2 kg, the difference in N_{ij} was not statistically significant (related-samples Wilcoxon signed rank test $P = 0.550$, $\alpha = 0.05$, mean N_{ij} of 0.136 at 1.6 kg and 0.138 at 2 kg).

Mean as well as maximum and minimum N_{ij} values for each condition are shown in **Fig. 1**. N_{ij} is lowest for the 6-G, 2-kg condition and increased as the acceleration was increased from 6 to 8 G. The effect of changing the helmet mass from 1.6 to 2 kg also affected the mean value slightly in the expected direction (e.g., mean N_{ij} was slightly lower for the 1.6-kg helmet than the 2-kg helmet). However, at an acceleration of 8 G, the 0.4-kg change in helmet mass had a near negligible effect on mean N_{ij}.

Specific anthropometric factors were analyzed to determine if they contributed to the observed neck responses. Female peak instantaneous N_{ij} values were not statistically different from male N_{ij} values in any of the three conditions (P-values ranged from 0.31 to 0.89). The effect of body mass on human neck response was also investigated. The average body mass of all subjects was approximately 80 kg. The neck response for subjects whose mass was above the mean (80 kg) were compared with the subjects with less than average body mass. The independent samples Mann-Whitney U-test indicated that no significant difference existed between the means for any of the three conditions (P-values ranged from 0.14 to 0.96). The effects of sitting height and neck circumference on neck response were also investigated using a similar method of dividing the group based upon the mean. Neither measurement had a statistically significant difference on the mean for any of the three experimental

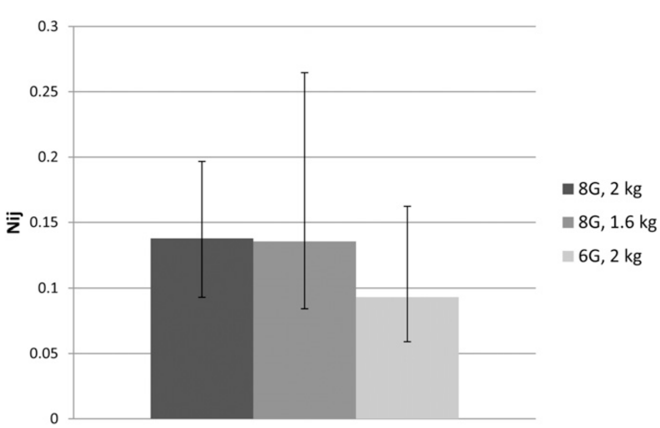

Fig. 1. Mean N_{ij} values shown as a function of each of the conditions (error bars show minimum and maximum values).

conditions, with the exception of sitting height in the 8-G/1.6-kg condition where subjects with low sitting height experienced higher N_{ij} values (P-values ranged from 0.016 to 0.85). Spearman's rank correlation was computed to determine the correlation between the N_{ij} values and the anthropometric conditions of body mass, sitting height, and neck circumference for each test setup. For the 8-G/2-kg condition, correlation of N_{ij} on body mass, sitting height, and neck circumference were −0.08, −0.25, and −0.07 respectively; for the 6-G/2-kg condition, correlations were −0.10, −0.25, and −0.19; and for the 8-G/1.6-kg condition correlations were −0.40, −0.55, and −0.34. No correlation between the anthropometric variables and N_{ij} were statistically significant at a confidence level of 0.05 with the exception of the effect of sitting height in the 8-G/1.6-kg condition.

Air Force aviation requires that a pilot have a 5% or less probability of an AIS 2 or greater injury during ejection. The relevant NHTSA risk curve is shown in **Fig. 2**. Unfortunately, the NHTSA risk curve does not provide a 5% prediction as it intercepts the Y-axis at 11.3%. Therefore, to understand the N_{ij} value that corresponds to the desired risk level, it is necessary to generate an alternate risk curve. Toward this end, a revised risk curve was generated using survival analysis, combining data from 67 human subjects in a single frontal impact experiment with 6 PMHS from a separate, but similarly structured, frontal impact experiment to obtain the human risk curve shown in Fig. 2. As shown, the human risk curve predicts a probability of injury at $N_{ij} = 0$ of only 0.52%, which is closer to the expected value of zero than the 11.3% probability produced by the NHTSA AIS 2 risk curve. Although the NHTSA risk curve predicts a 13% risk of AIS 2 or greater injury for the 8-G, 2-kg helmet condition mean N_{ij} of 0.138, no AIS 2 injuries were observed in the human subject population. The AIS 2 or greater human risk curve produced predicts a more accurate 0.91% risk of injury under these conditions. Additionally, the human risk curve indicates that the probability of neck injury increases much more rapidly as a function of N_{ij} than the NHTSA curve, reaching an asymptote near 100% probability at a N_{ij} of 3 as opposed to 6 for the NHTSA curve. Also shown in Fig. 2 is the 95% confidence interval for the human risk curve. Note that the NHTSA risk curve provides N_{ij} values outside of this confidence interval for values below 0.51 and greater than 1.85. Using inverse prediction, a 5% risk of AIS 2 neck injury using the human data risk curve gives an N_{ij} of 0.56 (95% confidence intervals of 0.129 and 0.998, respectively). The equation for the human AIS 2 risk curve is below.

$$P(\text{AIS} \geq 2) = \frac{1}{1 + e^{5.2545 - 4.1 * N_{ij}}}$$

NHTSA applied the AIS 3 risk curve to determine the N_{ij} performance limit for advanced automotive restraint systems and, thus, it is beneficial to compare their AIS 3 risk curve to a human subject data generated risk curve at this same AIS 3 level (see **Fig. 3**). The NHTSA AIS 3

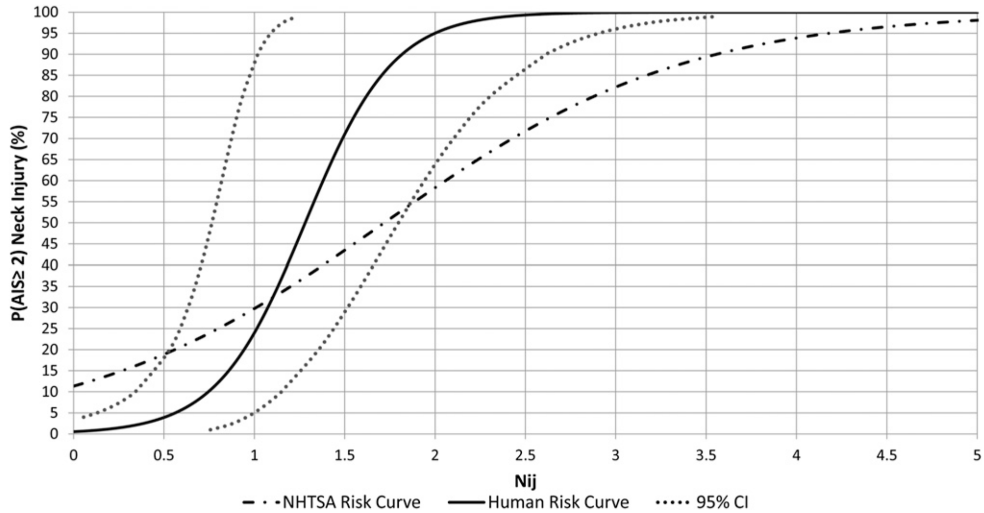

Fig. 2. Probability of AIS 2 or greater NHTSA and human N_{ij} neck injury risk curves (95% CI shown for human risk curve).

risk curve predicts 3.8% risk of AIS 3 neck injury or greater at zero input, thus it is better at predicting lower levels of risk compared to the NHTSA AIS 2 risk curve. Once again, a revised risk curve was generated using survival analysis, combining 67 human subjects from a single frontal impact experiment with 6 PMHS to obtain the human risk curve shown in Fig. 3. Unlike the results obtained for the AIS 2 curve, most of the NHTSA AIS 3 risk curve lies within the 95% confidence interval generated for the revised human risk curve with the exception of N_{ij} values below 0.2. Using inverse prediction, a 5% risk of AIS 3 neck injury using the human data risk curve gives a N_{ij} of 0.72 (95% confidence intervals of 0.165 and 1.274, respectively). A 22% risk of AIS 3 injury using the human data risk curve gives a N_{ij} of 1.23 (95% confidence intervals of 0.635 and 1.82, respectively) as compared to a N_{ij} of 1.0 for the NHTSA risk curves. As such, it would appear that the human data risk curve provides an intercept nearer the expected value of 0 and provides a less conservative estimate of risk than the NHTSA risk curves for a specified 22% risk of AIS 3 injury or greater. The equation for the human AIS 3 risk curve is below.

$$P(\text{AIS} \geq 3) = \frac{1}{1 + e^{5.31423 - 3.3922 * N_{ij}}}$$

A comparison of the human data generated AIS 2 risk curve and the AIS 3 risk curve is provided in **Fig. 4**. As stated previously the difference observed in the AIS 2 and 3 risk curves is produced by a single injury data point in the source data, indicating the sensitivity of the injury criteria when the sample size for the PMHS is small, as in this data set. These curves behave as would be expected. At the higher injury level, a greater value for N_{ij} is allowed at a specific risk level. For example, at 5% risk of injury, the AIS 2 risk curve allows for a $N_{ij} = 0.56$ and the AIS 3 risk curve allows for a $N_{ij} = 0.72$.

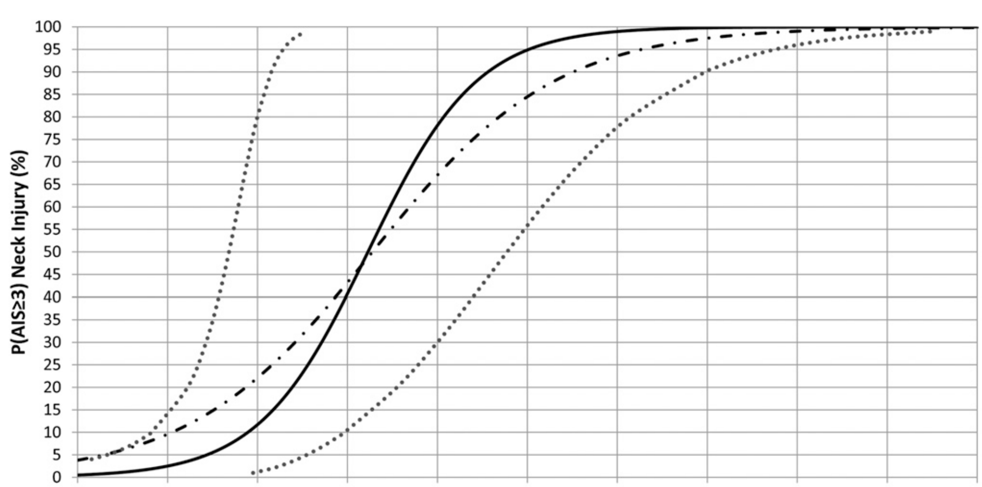

Fig. 3. Probability of AIS 3 or greater NHTSA and human N_{ij} neck injury risk curves (95% CI shown for human risk curve).

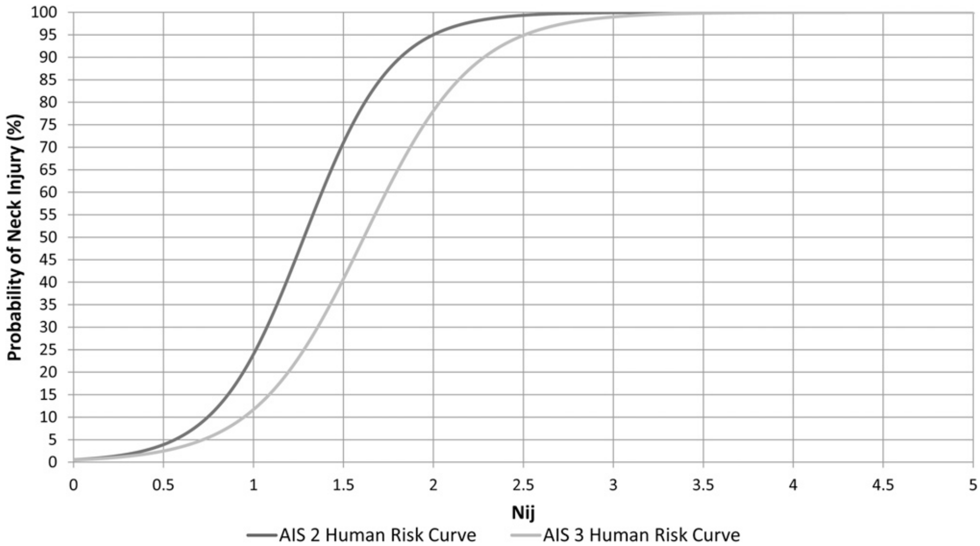

Fig. 4. Probability of AIS 2 or greater and AIS 3 or greater human N_{ij} neck injury risk curves.

DISCUSSION

This study sought to assess the applicability of the N_{ij} criteria to the evaluation of helmet systems of varying mass under various acceleration levels and to compare the NHTSA N_{ij} risk curves to human data constructed N_{ij} risk curves. When considering the neck response forces used in the N_{ij}, this study found that an increase in acceleration by 2 G had a greater impact on neck response than an increase in HMD mass of 0.45 kg. Although the change in helmet mass did not have a significant effect on N_{ij}, it is not clear whether this result is appropriate since the mass difference of the two test HMDs was relatively small. Whether this change in mass has a negligible effect on injury risk at the given acceleration levels or whether the N_{ij} does not appropriately account for an increase in risk requires further investigation.

Based upon the construct of the N_{ij}, which includes critical intercept values that normalize the criteria based upon varying occupant size, N_{ij} would not be expected to vary significantly based upon anthropometric differences related to size. That is, if the NHTSA intercept values are accurate, there should not be a statistically significant difference in N_{ij} due to gender, body mass, neck circumference, or sitting height. This study showed that the NHTSA intercept values did an adequate job of normalizing neck response for subject anthropometry based upon the observation that body mass, sitting height, and neck circumference were not significantly correlated with N_{ij} in any of the three test configurations, with the exception of sitting height in the 8-G, 1.6-kg test. Further supporting the finding that the critical intercept values satisfactorily compensate for anthropometric factors was the finding that subject gender did not have a significant effect on the resultant neck loads. Further, the neck loads were found not to be statistically significant between individuals with greater or less than average mass, neck circumference, or sitting height, with the exception of sitting height in the 8-G, 1.6-kg test.

The NHTSA N_{ij} neck injury criteria used paired piglet/ATD data to determine neck load and assess injury/no injury and then scaled this criteria to estimate human injury. However, other approaches have been applied. For instance, the AF tensile neck injury criterion combined data from noninjurious human subject data with PMHS injury data to construct a risk curve (7). In formulating these curves, human data (N = 208) was used for the noninjurious neck load data points and the PMHS data (N = 10) was used for the injurious neck load data points. The FAA has applied other methods, including pairing injury data from PMHS (N = 10) with the neck load data from an ES-2 ATD to create tensile neck injury criteria for qualifying side-facing aircraft seats (14). Each of these approaches has advantages and disadvantages. The combined human and PMHS method used in the AF tensile neck injury criterion has the advantage of a greater sample size (N = 218 vs. N = 10) compared to the PMHS only used by the FAA, which provides greater statistical power. It also directly estimates the neck load the subject experienced rather than assuming that the paired piglet/PMHS and ATD tests resulted in equivalent neck loading scenarios as the NHTSA N_{ij} and FAA side-facing seat methods assume. The disadvantage of the paired piglet/ATD and PMHS/ATD methods are the relatively small sample sizes in studies using PMHS based upon the availability and suitability of subjects. This small sample size makes statistical significance of the risk function and resultant injury criteria issues for use as a predictive tool.

As NHTSA's risk curves are not useful to determine the N_{ij} value for a 5% risk of AIS 2 injury as required for military aviation, it was necessary to generate revised human risk curves. A summary of the predicted N_{ij} values and N_{ij} values from the human AIS curves at key risk values are provided in **Table II**. The fact that the NHTSA curves were constructed with a smaller number of low N_{ij} values resulting in no injury appears to have resulted in AIS 2 and AIS 3 curves which overpredict

TABLE II. RISK CURVE PREDICTION VALUES.

Risk Curve	N_{ij} = 0 Injury Prediction	5% N_{ij} Prediction	22% N_{ij} Prediction
NHTSA AIS 2	11.3%	N/A	0.66
Human AIS 2	0.52%	0.56	0.97
NHTSA AIS 3	3.8%	0.114	1.0
Human AIS 3	0.49%	0.72	1.23

risk of injury at lower N_{ij} levels. Conversely, the human risk curves were constructed with many data points at lower N_{ij} values, which resulted in AIS curves which indicate human tolerance at moderate N_{ij} levels. Applying the AFLCMC escape system oversight office recommended 5% limit to the AIS 2 human risk curve would result in a maximum allowable N_{ij} value of 0.56. Although this value is relatively close to the performance limit of 0.5 which is currently being applied in this domain (22) with existing ATDs, as the limit calculated here has not been cross correlated with ATD response, caution should be taken when comparing these numbers.

This research analyzed different methods of constructing risk curves. For the combined human/PMHS method it was highlighted that for more statistical significance of the risk curves and resultant injury criteria, more PMHS testing is needed, with time history neck load data and injuries specified at the specific AIS levels. It is recommended that the test setup for the human and PMHS experiments be as close as possible, varying only input acceleration levels to achieve injurious results with the PMHS. Ultimately, this course of research might lead to an aviation specific, human data supported, neck injury criteria that would not only evaluate prototype HMD designs, but also provide design guidance parameters for the mass properties of future HMDs.

A few limitations of this study are worth noting. One issue in the area of human subject testing in accelerative environments is the use of small sample sizes. Testing of this kind is expensive, requires very comprehensive medical screening of volunteer subjects, and, in some cases, subjects remove themselves voluntarily from further testing for a variety of reasons, including neck discomfort. For example, of the 34 human subjects (16 women and 18 men) that participated in this particular $-G_x$ accelerative study, results were gathered for 9 women and 15 men for the 8-G, 1.6-kg HMD test, 9 women and 17 men for the 6-G, 2-kg test, and 7 women and 16 men for the 8-G, 2-kg condition. The power of the intrasample comparisons would have been greater if all subjects participated in all conditions. The overall sample size for the 3 test runs of 23, 24, and 26 subjects was further reduced when the group was divided to permit comparison of the effects of gender, body mass, neck circumference, and sitting height, further reducing the power of the statistical tests. In addition, the small number of PMHS injurious data points involved in the regression results in a statistically underpowered curve to be used to predict risk of neck injury. This study should be seen as a pilot study and additional injurious data should be included in the generation of the injury risk function before attempting to apply the curve to real world risk predictions. Additionally, this study only used human neck response data to generate the injury risk functions and did not attempt to relate neck loads observed in the Hybrid-III or other ATD with human neck injury as is done in the traditional application of the N_{ij} criteria. Since the Hybrid-III neck has been observed to be nonbiofidelic and not sensitive when used with head-mounted mass (2,25), application of the revised injury risk curves developed in this paper with a better suited ATD is necessary to apply this research in system evaluation. Furthermore, based upon the construct of the N_{ij}, this study considered only upper neck loads. Bass et al. found that added head-supported mass resulted in different head and neck kinematics compared with an unloaded head, resulting in greater injury potential to the lower neck (2). Future aviation-specific neck injury criteria should consider and potentially incorporate loading of the lower neck.

This paper advances knowledge in this area of study in two ways. First, by applying the N_{ij} to human subject data, important observations were made as to the sensitivity and appropriateness of this neck injury criterion to helmet mass, acceleration, and anthropometric factors. Second, generating injury risk curves using combined human and PMHS neck load data allowed for fruitful comparison and evaluation of the appropriateness of the NHTSA injury risk curves in the ejection environment.

The N_{ij} construct shows potential for use as an evaluative tool for HMD and escape system development as it embodies key characteristics, including a method to account for anthropometric differences and the ability to link probability of injury with restraint and helmet system imposed differences in neck response for at least conditions similar to frontal automotive crashes or the parachute shock portion of ejection. As a result, a revised form of this criterion evaluated through a more biofidelic ATD neck than the Hybrid-III may be useful as a tool to evaluate the overall neck load impact of different HMD loading conditions and different accelerations applied in the evaluation of new HMDs. Unfortunately, the N_{ij} is reactive rather than proactive when guiding HMD mass properties. That is, the criteria will provide information related to the acceptability of a fully prototyped HMD or escape system, but in its current format does not provide guidance to inform the design process. Besides the need to better understand the impact of helmet mass on this criterion, further advances, including adjustment to the formulation to account for the forces that are likely to occur for the remaining three phases of ejection and the ability to extend this criterion to provide predictive engineering tools are fruitful areas for further investigation. A larger scale study is now needed to further clarify these issues.

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