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Optimizing Critical Values and Combining Axes for Multi-Axial Neck Injury Criteria

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A PROPOSED METHOD TO RECTIFY THE MULTI-AXIS NECK INJURY CRITERION TO SUPPORT EJECTION SYSTEM VALIDATION

THESIS

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Abstract

The Air Force employs escape systems which include ejection seats in its high-performance aircraft. While these systems are intended to ensure aircrew safety, the ejection process subjects the aircrew to potentially injurious forces. System validation includes evaluation of forces against a standard which is linked to the probability of injury. The Multi-Axial Neck Injury Criteria (MANIC) was developed to account for forces in all six degrees of freedom. Unfortunately, the MANIC is applied to each of the three linear input directions separately and applies different criterion values for each direction. These three separate criteria create a lack of clarity regarding acceptable neck loading, leading to potential disputes during acquisition. Thus, the current research sought to adjust the MANIC formulation to provide clear, easy to interpret criterion values, and a single MANIC formula independent of the direction(s) of input acceleration. We developed an optimization program that would run the survival analysis for each of the input axes. Results from these optimizations were compared to an alternative formulation in which scaling factors for various critical values underwent a joint optimization, producing a single formulation, regardless of input axis. The feasibility of the joint optimization to produce a unified MANIC criterion are discussed as a potential method to develop a rectified MANIC which provided improved interpretability.

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A PROPOSED METHOD TO RECTIFY THE MULTI-AXIS NECK INJURY CRITERION TO SUPPORT EJECTION SYSTEM VALIDATION

I. Introduction

General Issue

Helmet Mounted Displays (HMDs) are becoming more prevalent in the cockpits of high-performance aircraft. They support three of the five strategic capabilities set out in the USAF Science and Technology Strategy for 2030, resilient information sharing, rapid and effective decision-making, and speed and reach of lethality [1]. HMDs increase pilots' capabilities in these areas, providing faster information conveyance. Specifically, these displays reduce the pilot's need to look down to in-cockpit displays and enable look-to-shoot missile locks; these ultimately enable faster effective decisions and actions. While these displays are currently in use in most tactical aircraft, including the F-35, F-18, F-16, F-15, A-10, as well as, many rotary wing aircraft, there is a push to expand the capabilities of these displays.

Unfortunately, the increased capabilities often result in increased weight and changes in the helmet's center of gravity, which increases the risk to aircrew safety, particularly during ejection. As program offices develop new or upgrade aircraft and HMDs, they need clear specifications and test procedures which reflect the likelihood and severity of aircrew injury during ejection events [2]. These specifications and test procedures must be applicable to the increasing envelope of personnel anthropometry, including reductions in the minimum height and weight requirements for pilots. The inclusion of smaller individuals increases the available pool of potential pilots, many of them female [3]. However, pilots of smaller stature may be more likely to experience neck injuries of greater magnitude due to increases in the relative HMD mass to the mass of bones and musculature in the neck. These injuries are especially likely in the ejection environment.

There is a definite need for an accurate way to measure the loads on the human neck during ejection, and to predict the risk of injury to the pilot based on the HMD and the pilot's size. The development of metrics to predict the risk of neck injury during ejection was progressed by Lt Col Parr in 2013 when he developed the first six-factor injury criterion called the Multi-Axial Neck Injury Criteria (MANIC). This work was a significant improvement from the previous evaluation criteria used by the armed services. However, there are some weaknesses in the current MANIC. The available measurement equipment and limitations in the size of existing data sets limited the original MANIC development. Recently, the Air Force Research Lab (AFRL) has initiated additional testing to overcome known deficiencies in the existing data. The improved data sets can be used to refine the MANIC for more accurate evaluations and predictions. Additionally, there is not an accurate transfer function to equate ATD (Anthropomorphic Test Devices) data to human equivalent loads. Captain Satava began the development of a transfer function, but this capability is incomplete. Finally, the MANIC is defined separately for each input axis while Developmental Testing (DT) involves ejection of ATD which undergo all axes of stimulation during a single test. Therefore, if an escape system and HMD paring provide MANIC values within the acceptable limits for two axes but fails by presenting MANIC values beyond these limits for the third during DT, it is unclear whether the system should pass [4]. This leads to disagreements or confusion during the acquisitions process, ultimately delaying the program and increasing potential cost overruns.

Problem Statement

The current methods applied for predicting neck injuries during ejection while performing DT are not sufficient. The current MANIC enhances the evaluation method as compared to previous methods. However, the fact that the metric is based upon limited data reduces its accuracy. Additionally, it is applied to each individual input axis, producing confusion, which adds time and cost to acquisition programs. Therefore, there is a need to revise the current MANIC to consider larger and more complete data sets. Most importantly, it needs to be developed into a tool that provides a single metric across all three input axes.

Research Objectives

The primary objective of this research is to evaluate the feasibility of a single metric which accounts for acceleration of a human or ATD in multiple axes, using independent axis input data, to classify neck injury risk for use in escape system evaluation. This work will focus on combining force and moment data resulting from acceleration of humans and post-mortem human subjects in the X and Y axes into a single value for evaluation. If successful, future work will need to explore the addition of Z axis acceleration. Other tasks that will be accomplished are evaluating the critical values to identify terms that are potentially unnecessary for certain axes and building a full six-factor AIS 2+ survivability curve for predicting the risk of injury to a pilot.

Research Focus

The primary benefactors from this research will be aircrew of future aircraft. Air Force decision makers will have a better tool, permitting more robust decision making regarding the risk of upper neck injuries during ejection for future aircraft ejection systems. Additionally, this research could benefit the aviation communities of the sister services, especially as we see more joint development programs like the Joint Strike Fighter. Finally, this research will benefit the Air Force's Life Cycle Management Center (AFLCMC) to reduce acquisitions cost and schedules when developing and evaluating escape systems and HMDs. Although targeted towards ejection system development, the work may additionally inform parachute and automotive collision evaluation methods.

Methodology

The data used will be test sled runs with humans accelerated at levels known not to cause injury, and test runs with PMHSs (Post-Mortem Human Subjects) at multiple acceleration levels to have non-injury and injury runs for each PMHS. A graph will be built with these test runs with the probability of injury on the vertical y-axis and the peak MANIC along the horizontal x-axis. A curve will be fit to the data points using a maximum likelihood fit to the logistic distribution resulting in an 'S' shaped curve.

Survivability analysis will be used to regress the survivability curves. And they will be compared to older curves from previous work. The AIS 2+ is our focus, but AIS 3+ curves may be built to be able to compare with previous work. Combining the MANIC calculations of the X and Y input axes will be attempted. A meaningful combination of the MANIC values from the two axes will be found. This single number will be the pass/fail criteria for a system and human combination.

Assumptions/Limitations

No new test runs will be performed; the data for the analysis will be provided by the 711th Human Performance Wing's Airman Biodynamics and Protection section.

Implications

This research will positively impact the Air Force by enabling better development and evaluation of escape systems thereby improving the safety of pilots. It will also develop better methods for interpreting and applying ejection test data in the acquisition process.

Preview

This thesis is structured with a scholarly approach, with the bulk of the information being in the form of articles that will be or have been submitted for conference publication. Chapter 2 will consist of a literature review, followed by two papers in Chapter 3 and 4, and finally a Conclusion in Chapter 5. The paper in Chapter 3 is titled "Importance of Mx in MANIC during Y acceleration" and has not yet been submitted. Chapter 4 contains the paper titled "Optimizing Critical Values and Combining Axes for Multi-Axial Neck Injury" and this has been submitted to the IISE conference and currently under review.

II. Literature Review

Chapter Overview

The risk to military aviation aircrew in ejection seat aircraft is increasing. The field is being opened to smaller pilots, who are predominately female. Additionally, the head worn equipment such as HMDs and night vision devices are increasing in weight. This creates a problem when calculating the risk to pilots during an ejection, which is an already difficult environment to predict. Additionally, the current testing of escape systems relies upon ATDs, however their response is not bio-fidelic and a transfer function is needed for accurate evaluations. The following literature review shows the current state of injury and risk prediction for ejections. It also highlights the shortcomings in the previously accomplished work. The literature points to shortcomings that include unpaired data sets between human and PMHS subjects, small sample sizes for PMHS data, equipment deficiencies in recording a full 6 degrees of freedom during acceleration tests, and unavailable time history for some data sets. Future research goals are to refine the 6 degree of freedom MANIC criterion developed by Lt Col Parr for more accurate evaluation and risk prediction of escape systems [5], and then to develop an ATD transfer function to allow accurate test and evaluation without human subjects.

Coordinate System and Accelerations

The common coordinate system used for this type of acceleration analysis is shown in Figure 1. This is the same one used for the Nij (NHTSA's Neck Injury Criteria), NIC (US Navy's Neck Injury Criteria), and MANIC. For these calculations, the point of reference used is the center of gravity of the head, instead of the torso as in the diagram. But the directions and corresponding moments are the same.

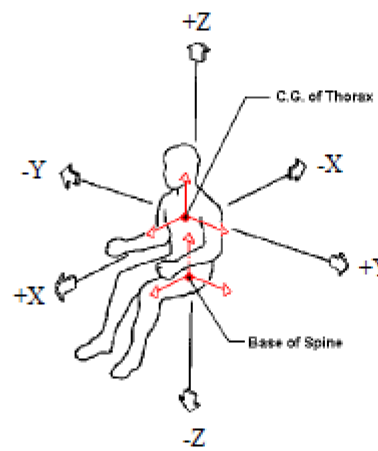

Figure 1. Human coordinate system from MIL-HDBK 516C Revision [4]

For x direction accelerations, the test subject is placed in an ejection seat that is mounted vertically and forward facing to a horizontal acceleration sled. Then the subject is accelerated forward in the positive x direction. The forces the participant experiences during a positive x acceleration are similar to the forces they would experience in a frontal impact car crash. For y direction accelerations, the test subject is placed in an ejection seat that is mounted vertically and side facing to a horizontal acceleration sled. Then the subject is accelerated laterally in the positive or negative y direction. The forces the participant experiences during y acceleration are similar to the forces they would experience if the ejection turned when entering the wind blast. For z direction accelerations, the subject is placed in an ejection seat that is either mounted vertically on a vertical acceleration or deceleration sled, or on the seat's back on a horizontal acceleration sled. Then the subject is accelerated towards the top of their head or dropped and use the impact interaction to drive a force from the seat-pan through head of the subject (similar to the observed vertical acceleration effects). This creates a compressive force on their head similar to the acceleration out of the cockpit during an ejection.

Description

The purpose for this literature review is to provide support for my work in refining the Multi Axial Neck Injury Criteria (MANIC) first developed by Lt Col Parr during his time at AFIT as a PhD student [5]. The MANIC's purpose is to classify the forces and moments placed on aircrew member's neck during an ejection and output a single value to be used to pass or fail an ejection system. This is the first and currently best method of accounting for all 6 degrees of freedom and computing a single value for evaluation. However, there are some short comings in this metric, which will be discussed in the following sections. These shortcomings include limited data for Mx, the fact that is based on small data sets, the fact that these data sets had limited time history data, and an inability to analyze and evaluate an acceleration event that involves more than one axis. This research seeks to build upon Lt Col Parr's work and refine the MANIC methodology. Additionally, after refining the MANIC, it will likely be necessary to build upon Captain Satava's work, as an AFIT Master's student, in developing a transform function to accurately relate Anthropomorphic Test Dummy (ATD) experienced loads to the loads a human would experience.

MANIC Development Background

As Parr discusses in his dissertation the current state of the head worn equipment for pilots includes increasing weight in the form of Helmet Mounted Displays (HMDs) and night visions devices [5]. The HMDs provide increased capability to pilots, but the added weight is a concern. The added weight is especially a concern as the field is being opened to increasing numbers of female pilots. While a positive trend for military aviation, females typically have less musculature in their shoulders and neck, potentially increasing their risk of injury in case of an ejection. The combination of increasing HMD mass and the inclusion of smaller pilots has raised concerns about pilot safety in the aviation community. In fact, concerns over the weight and design of the F-35 helmet were significant enough for Air Combat Command (ACC) to ground the F-35 fleet for a short time. Air Force Materiel Command (AFMC) has led a push to develop a multi-axial criterion for neck injury that also provides a way to evaluate ejection systems. Further support for developing a better criterion is the fact that historically programs have experienced delays and issues due to an inability to effectively evaluate ejection systems [7].

In his work Parr explores adoption of the Neck Injury Criteria (Nij) by NHTSA for automobiles in frontal crash accidents and the development of the US Navy Ejection Neck Injury Criteria (NIC) as a potential metric for F-35 ejection system evaluation. The Nij only provides evaluation in a single axis, but its basis is used in developing the MANIC. The NIC is good for providing accurate indicators of potentially high forces on each separate axis that could injure a pilot, but not a way to evaluate all axes together. When developing the MANIC function, data sets with all six degrees of freedom were measured. To develop metrics, paired human and Post-Mortem Human Subjects (PMHS) testing would be preferred to permit a better model by removing variability from the data set. Unfortunately, this was not available, so Parr carefully combined the data from previous human and PHMS studies to begin development of the MANIC. Frequently there was not paired test data of humans and PMHS, nor were there large sample sizes of PMHS data due to the expense and difficulty in conducting these studies. Additionally, some of the test runs did not have all axes or moments recorded, nor was there time history data for all runs. Nevertheless, Parr combined the available data to form a proposed criterion for participants experiencing acceleration along each of the three cardinal axes, as referenced in Figure 1.

Updated Tensile NIC

Parr also updated the USAF tensile Neck Injury Criteria. He used the most up to date PMHS tensile data available and combined it with data used previously for a total sample size of 22 human or PMHS runs. Due to the previous data, he was constrained to just calculate an AIS 3+ risk curve, instead of the AIS 2+ risk curve that is preferred by the military aviation community. His calculations compared well to the work the FAA performed in side-facing aircraft seats, providing predicted limits that were slightly lower. Ultimately, he recommended the new loading limit for tensile neck injury to be 1136 N for a 5% chance at AIS 3+, significantly lower than the previous limit of 1559 N. Unfortunately, he was restricted in having to use only the AIS 3+ injury curve because of the available data. Future work has been planned to gather new data for the building of an AIS 2+ risk curve. Specifically, the Airman Biodynamics and Protection section at the 711HPW is currently working on assembling a complete data set for additional analysis at an AIS Level 2+ level.

Injury Risk Curves for X axis input

Parr additionally applied the NHTSA Nij formula to the aviation escape environment with HMDs. The Nij was developed to quantify the forces on the neck of a vehicle occupant during a frontal collision. It is calculated with the simultaneous instantaneous peak Fx and My, and the Fx critical and My critical values. The measure is scaled based on occupant size and is calculated from ATD tests. The critical values are the level for a subject with a specified mass that would result in an AIS 3+ injury, so if the measured loads result in an Nij value of greater than 1, that system fails the criteria. AFLCMC requires the AIS 2+ level of injury, allowing for survival and evasion for aircrew that have to eject in combat. The study conducted by Parr included 73 human participants wearing helmets with varying masses and varying levels of G accelerations. To build survival curves, the data was combined with six PMHS data points. A potential problem with the PMHS data is that no time history was available, just the peak individual loads were available. Analysis showed that there was a significant difference in Nij values between 6 and 8 Gs with constant helmet weight of 2kg. There was no significant difference between helmet weights of 1.6 and 2 kg when the G's were constant at 6. This study did not try to relate ATD performance to human, it solely focused on human and PMHS data to build a risk curve. However, the critical values were developed from ATD data, which is not fully bio-fidelic. The takeaway for this pilot study is that the structure of the Nij has some potential for helping the aviation community.

Side Impact in Aircraft

Another study was performed to develop a lateral impact, upper neck injury criteria for use in designing military aviation escape systems and HMDs. It should be noted that lateral impact is especially useful for the rotary wing community [8]. This study works to address increasing weight of HMDs and expanding pilot populations to include shorter statures, and increasingly more females. The study incorporates human subjects as well as PMHS data. An AIS 2+ risk curve was developed to yield a 5% risk criteria. Additionally, an AIS 3+ risk curve was created. The full six factors were desired to build the MANIC, but due to a lack of observing Mx motion for humans in y acceleration that term was intentionally left out, so the MANIC is only made up of 5 factors and is called MANIC(Gy). LtCol Parr found that females experience a higher MANIC(Gy) score than males for both high G and low helmet weight and for the low G and high helmet weight. Additionally, body mass, sitting height, height, neck circumference and age were negatively correlated with MANIC(Gy) scores for both test configurations. These findings imply that as a person's size and mass increased, their MANIC(Gy) score was lower. Something to note from the different data sets is that the PMHS subjects were set in side-facing aircraft seats, while the human subjects were in standard ejection seats that were accelerated sideways, this could affect the accuracy of pairing the data together for constructing the risk curve. Takeaways from this study is that it appears that females and smaller people experience higher MANIC(Gy) scores and therefore increased risk of injury.

ATD Transform

Captain Satava studied the differences between the human and ATD response to Gy, lateral acceleration, and worked to build a transfer function for developing risk curves. The ATD data was all from the Hybrid III ATD neck, which is the most bio-fidelic ATD neck produced. However, this neck was design for evaluation systems during frontal impacts. The analysis showed that the loading between a human neck and an ATD neck is very different when applied in a side impact scenario. The ATD would bend to the side, while the human will roll and flex. Other findings were that male/female subject types were not normalized by the critical values as the critical values were designed to do, and multiple regression showed that females' responses were higher. Additionally, head supported mass (i.e., a helmet) caused a significant response increase for humans. Video confirmed the human neck response of flexing forward and rolling, with Mx highly correlated with Fx and Mz. Visually this looked like the human subjects were trying to 'look into their pocket', while the ATDs neck would strictly bend laterally and 'put their ear to their shoulder' [9]. Unfortunately, a significant amount of data used for Parr's MANIC did not include the sixth measurement of Mx due to the lack of observation in human test subjects. Poor data and nonequivalent responses keep the transfer function from being accurate, but Satava's work can be built on with better data sets that recorded a full six degrees of freedom. A transfer function in a different axis may be more feasible until a better ATD neck is developed.

Conclusions

The work done by Lt Col to develop the MANIC has been very influential and has advanced the ability for decision makers to evaluate escape systems and the effect of HMDs. Likewise, Captain Satava has continued the process of transforming ATD data to human equivalents which has the potential to greatly help the acquisition and aviation safety community. With increased fidelity in data sets from AFRL, a more accurate MANIC function and AIS 2+ risk curves can be developed. This will eliminate the issues of unpaired human and PMHS data, unavailable time history data, and missing load data.

Additionally, the work towards an ATD to human transfer function can be progressed with the better data and by focusing on an axis with more closely matched responses.

III. Importance of Mx in MANIC during Y acceleration

1. Introduction

Ejection based escape systems are employed on most high-performance aircraft to raise personnel survivability during a catastrophic event. Unfortunately, the nature of an ejection event places elevated and complicated loads on the individual that could cause injury [5]. A pilot can experience forces in all three directional axes. As the head pivots on the neck, these forces exert forces, along with the associated moments, on the human neck during an ejection event. Any one of these loads or moments has the potential to cause an injury to the individual's spine or neck. Complex tools are needed to analyze this environment and predict the likelihood and severity of an injury from ejection during acquisition of aircraft with integrated escape systems.

Recently Parr and colleagues developed the Multi-Axial Neck Injury Criteria (MANIC) for application to the ejection environment [6]. This metric has been adopted by the Air Force Lifecycle Management Center (AFLCMC) for evaluating ejection-based escape systems. The MANIC works by calculating a number from all three forces and all three moments about the occipital condyles as a function of time. In the calculation it uses critical values related to injury in denominator terms to normalize the force and moment values. The equation was developed based upon and extends the Neck Injury Criteria (Nij) from the National Highway Traffic Safety Administration (NHTSA) [7]. The Nij was developed to predict the likelihood of injury during frontal car crashes. It only included what was expected to be the three largest contributors to injury in a frontal crash, the force exerted on the upper neck in the x axis (Fx), the tensile force exerted in the z axis (F_z) and the moment about the y axis (M_y). The Nij was calibrated to predict injury on an Abbreviated Injury Scale (AIS) Level 3, and the critical values were selected such that a value of 1 corresponded to a 20% chance of an AIS 3 injury. The development of the MANIC required adjusting current terms and adding additional terms. AFLCMC desired prediction of a 5% chance of injury on the AIS Level 2 scale, a lower level of injury than applied in the Nij [6]. Additionally, with ejections being more dynamic than a frontal crash, it was necessary to include additional degrees of freedom within the metric.

Because of the cost and risk of testing actual ejection sequences with live humans, testing to develop these metrics was performed on single direction test tracks with humans at accelerations below the injury threshold and with Post-Mortem Human Subjects (PHMS) at accelerations above the injury thresholds. In Parr's original formulation of the MANIC for y axis acceleration, he included five of the six degrees of freedom, omitting Mx due to lack of observed responses. To combine the results for the three individual axes of acceleration tests, it will be important that all potential forces and moments be included in the metric for each axis. Therefore, this paper will investigate the effects of including the Mx term on the MANIC equation results for y axis accelerations. Additionally, the paper will investigate the effect of using the table critical values versus linear fits for the critical values.

2. Methods

Data was selected from a mix of human subjects, which are typically uninjured, and PMHS. The PMHS are typically exposed to higher accelerations than live human subjects, including accelerations that will result in soft tissue tears or bone fractures corresponding to injury. The PMHS data used here was also used in previous MANIC research and was previously described [7], as was the human data. The data was structured in spreadsheets with separate columns for forces, moments, and time. Each test run had its own spreadsheet. Separate spreadsheets were built with the test run number, subject mass, and injury results. The acceleration data included data for all three forces and moments.

The current research incorporated all six terms of the MANIC equation in our analysis when available. Previous work by Parr excluded Mx for the Y axis due to a lack of observing Mx during previous tests. However, these values are readily available in the newer data sets, allowing us to explore the significance of the Mx term.

Four different sets of survival analysis were performed. The survival analysis was run with and without the Mx term. Additionally, the survival analysis was run with critical values from the table and run with the linear fits for comparison. The method of using linear fits has been previously established by Williams [11]. This resulted in four survival analyses each with a corresponding MANIC cutoff value for a 5% chance of AIS Level 2 injury.

3. Results

Table 1 shows the resulting MANIC cutoff values from the survival analyses. Including the Mx term results in an increase in the cutoff value for the data set using linear fits for the critical values. The increase of the injury cutoff value shows the result of the survival analysis curve being shifted to the left by the inclusion of the Mx term. The difference in cutoff values is expected with the inclusion of the additional moment. However, the values for the analysis with the tabular critical values does not change. This suggests that the resulting MANIC is influenced more by the critical values being from the table, than the inclusion or removal of Mx.

Mx & Table/Line fit Sensitivity		
	w/o Mx	w/ Mx
Linear Fits	0.4752	0.6451
Table values	0.6444	0.6444

Table 1: MANIC values at a 5% chance of AIS Level 2 injury.

Survival Analysis curves can be seen in Figures 2 and 3 below. Figure 2 is the original curve without Mx and the new curve with Mx included, both with linear fits. The slope with the addition of Mx is significantly changed, due to some of the non-injurious points being higher in MANIC as a result of adding the Mx term.

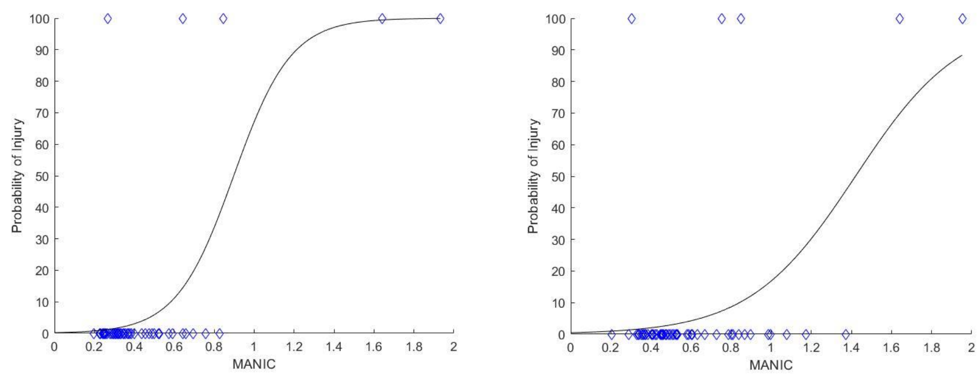

Figure 2: SA Curves for Mx Comparison. Left graph has Mx removed, right graph has Mx included. Both use linear fits for the critical values.

Figure 3 shows the comparison of the critical values from the table on the left, and the critical values from the linear fits on the right. No noticeable difference is seen between them, and from Table 1, the cutoff values are very close to one another.

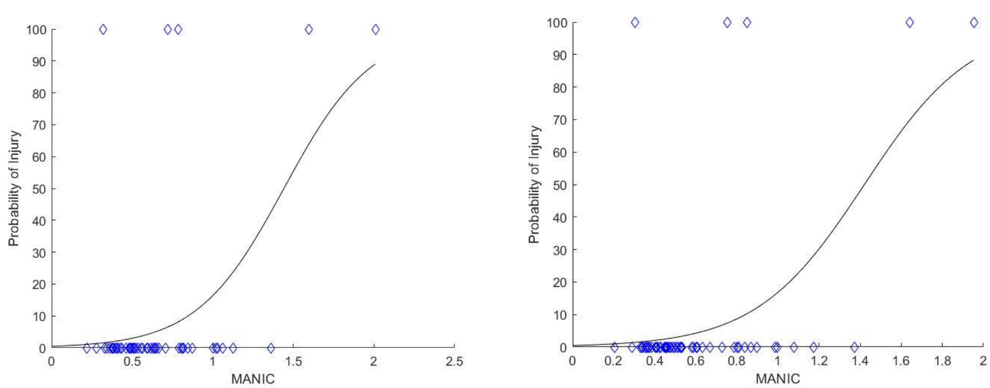

Figure 3: SA Curves for critical value source comparison. Left graph uses critical values from the table, right graph uses linear fits for the critical values. Both include the Mx term.

Another noteworthy result is the similarity in the cutoff value between the current analysis and what was found by Parr. The MANIC value equating to a 5% chance of AIS Level 2 injury found by Parr was 0.48. This current survival analysis using the linear fit to find a more precise match of critical value to the subjects' mass and without the Mx also produces a value of 0.48. However, the analysis with the critical values from the table have a cutoff value of .64, which is higher than what was found by Parr.

4. Discussion

When Parr first studied the MANIC applied to accelerations in the y direction, he removed Mx because no true Mx rotation was observed during video of humans under later acceleration. There was significant My and Mz motions coupled with some Mx motion. Due to some observations with x direction and y direction data combined, it appeared that the Mx term was potentially a significant indicator of injury. Comparing the results of the survival analysis with and without the Mx term, it does not appear that the Mx term has a significant effect for y axis accelerations because there is only a small change in the cutoff value. Additionally, from the correlation graph in Figure 4, the MANIC score without the Mx term correlate to the scores with the Mx term, although the slopes of these lines differ somewhat between the human and PMHS data points.

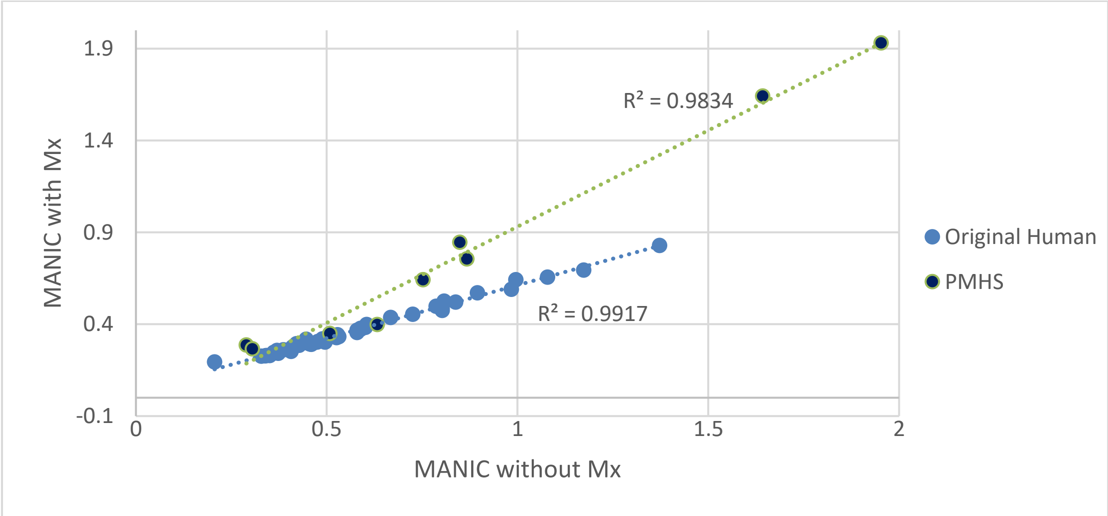

Figure 4: Correlation graph of Mx term for MANIC scores.

The shape of the second curve from Figure 3 is expected. The addition of the sixth term raises the MANIC score for the non-injurious data, this flattens the curve. If additional injurious data points were inserted in the data set, it is expected to improve the shape of the graph and improve its accuracy.

Another observation of note, even with the difference of the critical value calculation methods, the same cutoff value was found. Also, when the Mx term was varied for the table values the cutoff value was the same, unlike for the linear fits. This could mean that the selection of critical values from the table could influence the resulting MANIC.

5. Conclusion

From the results, it does not appear that Mx is a strong contributor to chance of injury for accelerations in the y direction. Inclusion of additional injurious test runs with all six degrees of freedom measured would increase the accuracy of the survival analysis calculations and MANIC cutoff values. Also, more injurious points from robust tests are needed to help define the upper end of the survival curve for an accurate estimate of injury risk. Additional non-injurious human test data with all six degrees of freedom would also strengthen the survival analysis and MANIC calculations. Finally, it also appears that the linear fits for the critical values do provide a more precise calculation of MANIC scores.

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IV. Optimizing Critical Values and Combining Axes for Multi-Axial Neck Injury

Abstract

The Air Force employs escape systems, which include ejection seats, in its high-performance aircraft. While these systems are intended to ensure aircrew safety, the ejection process subjects the aircrew to potentially injurious forces. System validation includes evaluation of forces against a standard which is linked to the probability of injury. The Muti-Axial Neck Injury Criteria (MANIC) was developed to account for forces in all six degrees of freedom. Unfortunately, the MANIC is applied to each of the three linear input directions separately and applies different criterion values for each direction. These three separate criteria create a lack of clarity regarding acceptable neck loading, leading to potential disputes during acquisition. Thus, the current research sought to adjust the MANIC formulation to provide clear, easy to interpret, criterion values and a single MANIC formula independent of the direction(s) of input acceleration. We developed an optimization program that would run the survival analysis for each of the input axes. These results were compared to an alternative formulation in which scaling factors for various critical values underwent a joint optimization, producing a single formulation, regardless of input axis. These results are compared and the feasibility of the joint optimization to produce a unified MANIC criterion are discussed as a potential method to increase the interpretability of the MANIC.

Keywords
Optimization, survival analysis, safety, neck injury, test and evaluation

1. Introduction

Ejection systems are included in most high-performance aircraft to improve the personnel survivability during catastrophic events [5]. Unfortunately, the individual experiences the ejection sequence as a complicated series of musculoskeletal loads. During the initial phase of ejection, as the seat accelerates upward out of the aircraft, the pilot’s neck and spine are compressed in the vertical, z axis. Assuming the ejection seat remains facing forward, the wind blast exerts a strong load in the x direction, like the loads experienced during a frontal car crash. However, if the ejection seat turns, that windblast can exert loads in the lateral, y axis. Wind can also enter the helmet, placing a tensile force on the neck and spine in the z axis. Therefore, the pilot can experience high loading in all three major axes during ejection from the aircraft. The end of the ejection sequence results in additional loading from the parachute deployment and opening shock, which typically presents a compressive force in the z direction [5]. Any of these forces or their combination can result in spinal or neck injury [4]. Tools are required to understand the likelihood of injury from the loads experienced by the pilot to support development of safe ejection systems.

Complex tools are needed to analyze this combination of loads experienced by the pilot. Recently, the Multi-Axial Neck Injury Criteria (MANIC) was proposed by Parr and colleagues [8]. A version of this criteria was adopted by the Air Force Lifecycle Management Center (AFLCMC) for evaluating ejection-based escape systems for modern high-performance aircraft [4]. The MANIC calculates the forces and moments exerted at the upper neck in all three axes, as a function of time. These forces and moments are each normalized by a critical value, which is an estimate of the force or moment value which would likely induce injury. This formulation was inspired by the National Highway Traffic Safety Administration's (NHTSA) Neck Injury Criteria, referred to the N_{ij} [9]. The maximum MANIC value during an ejection sequence is then used to estimate the likelihood of injury. To develop this criterion, the likelihood that an individual will experience a specified level of injury is estimated based upon existing experimental data collected from human and post-mortem human subjects (PMHS) using survival analysis. The Nij was developed to account for the three largest factors contributing to injury in a frontal automobile crash, which are the force exerted in the upper neck in the x axis (i.e., Fx), the force exerted in the z axis (i.e., F_z) and the moment about the y axis (i.e., M_y). The equation for N_{ij} used critical values developed from extensive testing that were closely related to the force level that would lead to a 20% chance of injury at an Abbreviated Injury Scale (AIS) Level 3, permitting the N_{ij} to produce a corresponding value of 1.

To extend this metric to assess ejection systems for the F35 Joint Strike Fighter (JSF), a panel of subject matter experts selected critical values for the remaining upper neck forces and moments to use in a family of early metrics based upon limited experimental evidence. The MANIC adopted these same critical values. As specified by the United States Department of Defense, the ejection system should have less than a 5% probability of producing an AIS Level 2 injury. Thus, the permissible MANIC value was derived by applying survival analysis to a combination of existing human and Post-Mortem Human Subject (PMHS) data to determine the MANIC value corresponding to the probability and severity of injury.

Due to the difficulty, risk, and cost associated with conducting experiments using actual ejections, the experiments used to develop the MANIC were simplified. Individual test runs were performed with different laboratory apparatus, where each apparatus was designed to expose the test specimens (human or PMHS subjects) to accelerations in one of the three axes. As a result, a different MANIC equation and criteria were developed for each axis, leading to MANIC values of 0.56 for the x axis [9] and 0.48 for the y axis [7]. This effort provided a set of criteria, simplifying system test, evaluation, and specification. However, it remains necessary to calculate three individual criteria to evaluate a system. As it is unclear which of the MANIC values apply to any segment of the ejection sequence, the existence of these three individual criteria sometimes leads to disputes regarding the sufficiency of an ejection system, particularly when this system can provide MANIC values significantly below the critical MANIC value in some but not all three axes. Further, the resulting criteria may each be biased as they assume that the individual is only exposed to forces in one direction at any moment in time.

Measuring the loads on aircrew necks during ejection events is becoming increasingly important as Helmet Mounted Displays (HMDs) become more prevalent, placing additional mass on the pilot's head. Additionally, pilot anthropomorphic ranges are increasing to include individuals of smaller and larger stature. The current MANIC equation combines forces and moments at the upper neck for all six degrees of freedom and returns a single value. Incorporating all six axes into this single metric permitted it to replace most of the prior metrics that were applied by the Air Force Lifecycle Management Center (AFLCMC) for evaluating ejection-based escape systems. However, it is necessary to simplify the application of this metric, such that a single, clear, criteria can be applied to assess ejection systems. This research seeks to modify the MANIC so that a single, universal criteria is provided. This will give decision makers in acquisitions a simpler and clearer rule to apply when evaluating escape systems.

2. Methods

2.1 Data Source and Structure

To support the analysis of our current research, it was important to select data from a mix of human subjects, which are typically uninjured humans and PMHS. The PMHS are typically exposed to accelerations which result in soft tissue tears or bone fractures corresponding to injury. Further, it was important to include data from acceleration tests in at least two axes. Data from X axis acceleration tests were adopted from previous MANIC research and has been described previously [8]. The PMHS data for the Y axis was also used in previous MANIC research and was also previously described [7]. The data was structured in spreadsheets with separate columns for forces, moments, and time. Each test run had its own spreadsheet. Separate spreadsheets were built with the test run number, subject mass, and injury results. The data for the X axis acceleration only contained measured values for the Fx and Fz and My values, forcing the assumption that Fy, as well as Mx and Mz were negligible. The Y axis acceleration data included data for all three forces and moments.

2.2 Analysis Philosophy and Approach

In the current analysis, we sought to develop a method to adjust the MANIC formulation which simplifies its application. First, we wish to redefine the MANIC formulation such that each of the critical values can be scaled. This requires us to define the MANIC formula as shown in Eqn 1.

$$MANIC = \sqrt{\left(\frac{F_x}{p_1 * Fxcr}\right)^2 + \left(\frac{F_y}{p_2 * Fycr}\right)^2 + \left(\frac{F_z}{p_3 * Fzcr}\right)^2 + \left(\frac{M_x}{p_4 * Mxcr}\right)^2 + \left(\frac{M_y}{p_5 * Mycr}\right)^2 + \left(\frac{M_z}{p_6 * Mzcr}\right)^2} \quad (1)$$

In this equation, each of the critical values are scaled by an appropriate parameter (p_1 through p_6). The remaining parameters in Equation 1 were present in the original MANIC formulation, where the forces in the upper neck are represented by F_x, F_y, and F_z, the moments in the upper neck are represented by M_x, M_y, and M_z, and the critical values are represented by the F or M values in the denominator of each term, annotated with the subscript cr. In the current research, we assume p_1 through p_6 can be derived to provide MANIC values with specific desirable qualities.

In a first analysis step, we assume that the original critical values were selected such that the relative values of each of the critical values were correct. Therefore, we assume that each of the new parameters added to the MANIC formulation are equal. These values are then scaled such that a MANIC value of 1 will correspond to a 5% chance of an AIS Level 2 injury. In subsequent analyses we then assume that the critical values were not correctly chosen, such that their relative values provide an inappropriate scaling. For this reason, we expect the dominant forces created by acceleration in the X-axis to result in a first MANIC value at a 5% chance of an AIS2 injury while dominant forces created by acceleration in the Y-axis will result in a second, different MANIC value for the same injury probability and level. Under this condition, it becomes necessary to assume that the parameters p1 through p6 will differ from one another.

2.3 MANIC Calculations

Overall, the goal was to optimize the values of the parameters p_1 through p_6 such that interpretation of the modified MANIC was simplified. The approach developed in this research is depicted in Figure 5. As shown, the first step of this approach was to fit linear equations to the critical values which are provided as a function of mass of the test participant, as suggested previously [10]. The modified MANIC equation shown as Equation 1 was then applied to calculate the peak MANIC for each experimental run. Survival analysis is then applied to fit a survival function to the data given the injurious and non-injurious data in the data set [11]. The resulting curve is then used to calculate the MANIC value which corresponds to a 5% probability of an AIS Level 2 injury. This computation was originally computed using parameter values all equal to 1, resulting in a critical MANIC value, at which one would expect injury to occur. To simplify interpretation, the initial optimization adjusted the parameters such that the resulting MANIC value would be equal to 1. Thus, an optimization was performed to determine the parameter values which would result in a critical MANIC value of 1 at a 5% probability of AIS2. All calculations were performed using MATLAB 2020a.

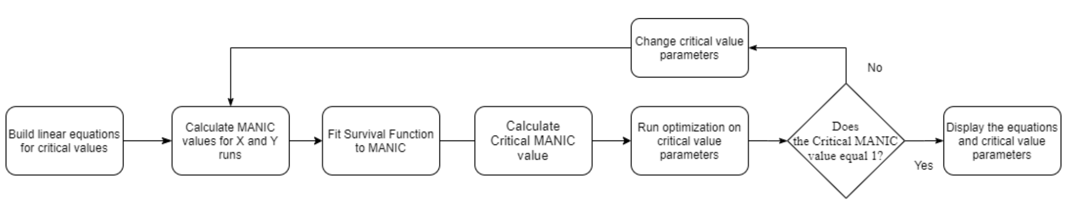

Figure 5: Flow chart of calculations and steps for the optimization and survival analysis

Equation 2 below shows the form for calculating the probability of injury from the MANIC score. The parameters 'a' and 'b' are calculated from the Matlab code for the Survival Analysis curve fit and specific values will be given for the Survival Analysis curves later in the paper.

$$Probability\ of\ Injury = \frac{1}{1+e^{\frac{-(MANIC-a)}{b}}} \qquad (2)$$

For this work, we assume that a straight line is the best method to estimate the critical values. Additionally, we assume that the relationships between the slopes and intercepts should not change. Therefore, multipliers in the denominators of the terms in the MANIC equation were used. This allows us to influence the final MANIC number without changing the relative critical value equations as a function of participant mass, as assumed by subject matter experts during the initial development of the N_{ij}. It should also be noted that the optimization utilized the combined data set from the X and Y axis acceleration conditions. Thus, the optimization seeks to find a single set of parameter values which provide a single MANIC value regardless of the input axis.

A total of three optimizations were performed. The first utilized a single value for all parameters. This optimization maintained the relationship between the critical values and simply offset the maximum MANIC value to achieve a criteria value of 1.0. This was intended to simplify specification of the test criteria as an escape system providing a MANIC value greater than 1.0 would be assumed to fail the qualification test. The second optimization permitted the parameter for the force terms (p1, p2, and p3) to vary separately from the moment terms (p4, p5, and p6). This manipulation was performed since the force and moments are specified with different units. The third scenario permitted all parameters to vary independently. The compilation of code was able to successfully compute the MANIC values with the linear equations for the critical values, run the survival analysis, analyze the MANIC value, and adjust the denominator parameters to obtain a MANIC value of 1 at a 5% chance of an AIS level 2 injury for all cases.

3. Results

Table 2 contains the parameters for the four optimizations. From early analysis using the full six terms for the MANIC equation and the newer Y-axis data, the parameter value from the optimization which produces a MANIC of 1.0 at a 5% probability of an AIS 2 injury is 0.6748 for the X-axis and 0.6451 for the Y-axis. When both axes are combined, the parameter value is 0.6598 as shown in Table 2. Applying this parameter simply shifts the survival analysis curve to provide this more intuitive cutoff value. However, this analysis does not permit any adjustment to account for any error in the critical values which might produce differences in the different parameter values for the X and Y axis acceleration conditions.

Table 2: Table of the different multiplier values for the three optimization scenarios.

Optimization	p1	p2	p3	p4	p5	p6
p1=p2=p3=p4=p5=p6	0.6598	0.6598	0.6598	0.6598	0.6598	0.6598
p1=p2=p3, p4=p5=p6	1.1124	1.1124	1.1124	0.5132	0.5132	0.5132
p1≠p2≠p3≠p4≠p5≠p8	0.9286	0.9611	1.1468	0.3766	1.0174	1.2251

Permitting p1, p2, and p3 to vary separately from p4, p5, and p6, results in a larger parameter value for the force parameter than the moment parameter, indicating that perhaps the critical values for the forces are not large enough relative to the moment critical values. Finally, allowing each parameter to vary independently increases p3 and p6 noticeably, while p4 falls well below 1.

Figure 6 shows the maximum MANIC values as a function of participant mass for the original values, as compared to the maximum MANIC values for three of the optimization conditions. As shown, the original MANIC values are less than the optimized values, except for Scenario 3. This change shifts the survival curve to the left permitting the MANIC value with a 5% chance of an AIS 2 injury to be increased to 1.

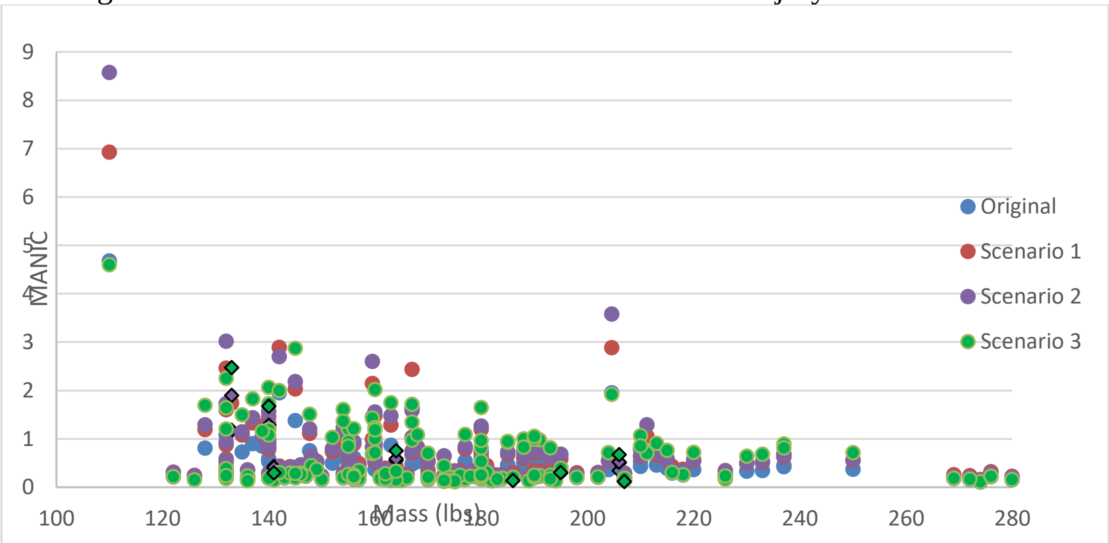

Figure 6: Graph showing the maximum MANIC values for the original calculations and Optimization scenarios 1, 2, and 3.

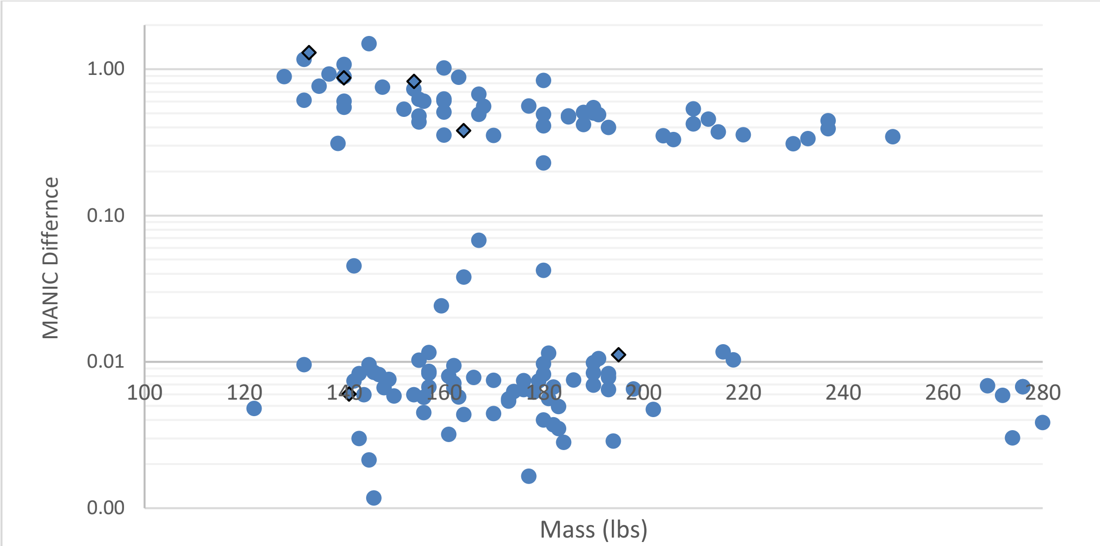

Figure 7: Graph showing the difference in MANIC between the original calculations and optimization scenario 4 in the right panel. Data points represented by outlined diamonds signify injurious trials while the circles represent non-injurious trials.

Figure 7 shows the difference between the optimized maximum MANIC values determined in Optimization scenario 3 from the MANIC values using the original MANIC formulation, plotted on a semi log plot. The use of the semi log plot improves the visibility of small changes which occur when both the original and optimized MANIC values are small. Comparing Figure 6 and Figure 7, we see that the difference in MANIC values is related to the initial magnitude. Also, there is not an obvious influence of subject mass upon the differences in MANIC values.

4. Discussion

The decision to Multiply the denominators in the MANIC equation by individual constants was made for two reasons. First, we needed to adjust the MANIC values and adjusting the denominators in the equation allowed this goal to be achieved, while also being able to adjust individual terms if desired. Second, by multiplying the denominator values, we would influence the effective relative differences between the critical values without changing the relationship between critical values and participant mass. An initial attempt involved changing the slopes and intercepts of the critical value-mass relationships. However, this manipulation produced significant changes in both the intercepts and slopes of the functions, making interpretation of the relative changes in critical value difficult. Therefore, a multiplier was added to the denominator. This preserves the relative differences in critical values as a function of mass, consistent with the N_{ij} and MANIC formulations.

In Optimization scenario 2, the force parameter multiplier was higher than the moment parameter, indicating that the relative values for the force critical values to the moment critical values may be smaller than desired. This indicates that the forces have less of an effect than the moments on the magnitude of the resulting MANIC. The final two optimization scenarios indicate that the critical values for Fx and My may be much smaller relative to the other parameters than is optimal. At first, this finding may seem counter intuitive. The original analyses produced by Parr and colleagues indicated that the MANIC values which result in injury for the X input axis was very close to the MANIC values, which would result in injury for the Y input axis (i.e., 0.56 [9] as compared to 0.48 [7]). However, in that analysis the input data set for they Y axis did not include the moments about the x axis. When this value was included in the present analysis, the unadjusted MANIC value increased from 0.48 to 0.65. This would indicate that injury occurs at higher original MANIC values when the neck is exposed predominantly to y axis forces and x axis moments, as was the case for the Y axis acceleration, than when the neck is exposed to predominantly x axis forces and y axis moments, as was the case for the X axis acceleration. Thus, the larger parameters, which were found in the later optimization scenarios, permit the critical values to be adjusted to adjust for this difference. Figure 8 below shows the shift in the survival curves that results from the optimization. Also shown is that the injurious points from the Y axis input are predominantly to the left of the points from the X axis input in the original MANIC formulation. However, these values are intermingled in the optimized formulation. Thus, the optimization approach is compensating for differences in the injurious MANIC values between the two input axes.

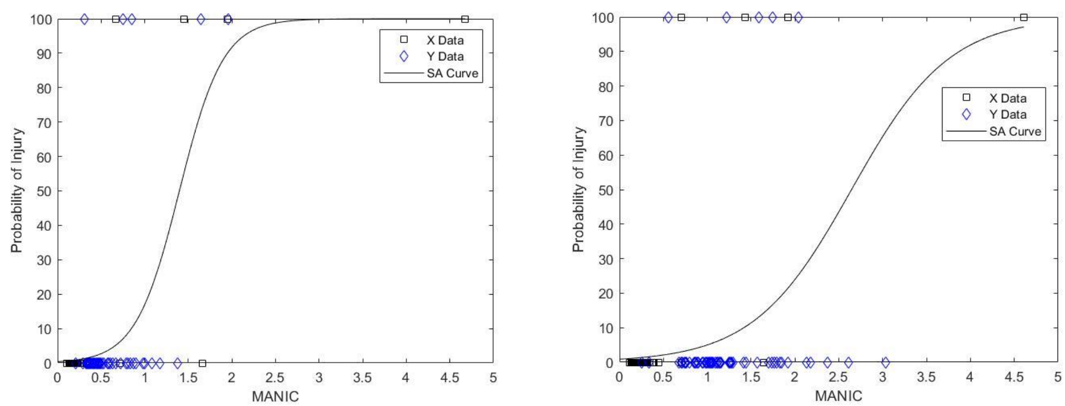

Figure 8: Survival Analysis Curves. Results for the original MANIC Equation shown on the left. Optimized MANIC Equation from optimization scenario 3 shown on the right. Black squares are X direction test points. Blue diamonds are Y direction test points. For the original calculations, the SA curve parameters are: a = 1.3975, b = .2506. For the optimized calculations, the SA curve parameters are: a = 2.6448, b = .5586.

While the optimization method shows promise in reconciling differences in neck response and injury thresholds to acceleration in different input axes, the results from this analysis are insufficient to advise a change in the current MANIC formulation. The currently available data is simply insufficient. The existing data has incomplete force and moment information for the neck in response to acceleration along the x direction; only the Fx, Fz, and My were recorded. Additionally, there is no data with time histories available for the PMHS in response to x axis acceleration. Nor are there enough injurious test points for the x or y axes. Additionally, insufficient data exists for the input accelerations in the z axis. Finally, the current method optimizes the MANIC values based upon data from single axis inputs while the ejection sequence is much more complex. Ideally any optimized MANIC equation would be verified based upon tests which better emulate an actual ejection. However, it is recognized that such an experiment would be difficult to conduct in a controlled fashion and head accelerations are not currently monitored during real world ejections. Finally, previous research has shown that available Anthropomorphic Test Devices (ATDs) do not exhibit a bio-fidelic neck response, particularly in response to y axis acceleration. Thus, it will be necessary to define a robust transform function to transform ATD response to better represent the response of humans [12].

5. Conclusion

We have demonstrated a potential method for improving the MANIC formulation for evaluating escape systems and informing acquisition decisions. This method employed optimization on parameters within the MANIC equation to reconcile differences in the MANIC threshold in response to x and y axis acceleration. If additional data for x and z axis acceleration were available, this method could potentially be applied to provide a single MANIC formulation to support analysis of forces and moments about the upper neck in response to complex accelerations, such as those experienced during ejection. Once all three axes are incorporated, work can then begin on applying it to a more realistic ejection environment, considering additional complicating factors such as the lack of ATD bio-fidelity.

Disclaimer

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the U.S. Air Force, the Department of Defense, or the U.S. Government.

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V. Conclusions and Recommendations

Conclusions of Research

From Chapter 3 of this document, the effect the Mx term has on injury for y axis acceleration is not significant. Although this term should not be completely disregarded for cervical injury research. The Mx term may have significant effects for accelerations in the x or z direction. Additionally, as work progresses to combine the analysis of the three axes, it should be included for thoroughness.

Also, from Chapter 3, there is value in using the linear fits for the critical value over using the table values. While the table values work for ATD testing, the linear fits will provide the most accuracy for human and PHMS testing. With humans being the ultimate subject for ejections, the linear fits should be used for calculations.

The work done for the paper in Chapter 4 showed that it is possible to calculate MANIC for more than one axis at a time. Combining x and y direction accelerations in the same calculations shows promise for being able to calculate all three directions together, to improve the MANIC tool for predicting cervical injuries. This is a significant step for MANIC to become a tool to evaluate a full ejection sequence.

Additionally, in Chapter 4, the optimization was successful in handling not only a single axis, which would improve the MANIC tool as an evaluation criterion. But it was also able to successfully optimize the equation for two axes, providing another step forward to being able to provide an easily communicated tool for evaluating a full ejection sequence.

Significance of Research

The goal of this research was to develop a method that could improve the MANIC for evaluating ejection seat injury chances. This goal has been accomplished. The first way this was done was with combining the x and y axes together for evaluation. In the past, each axis had to be analyzed separately. An actual ejection however puts the pilot through all three acceleration directions in one combined event. Being able to combine the two axes together brings us a step closer to combining all three.

A metric derived from such a method would permit us to analyze a full ejection sequence with a single tool. This will enable the best prediction of pilot injury, allowing the acquisition community to build the best escape systems for high performance aircraft. The second way we accomplished our goal was using an optimization to have the survival analysis return an easily communicated criteria for the desired chance of injury. This will allow development and acquisitions personnel to more easily communicate across teams and to decision makers the capabilities of escape systems. The combination of these two methods was also successful and combining them has the potential for creating a greater impact for evaluating and developing ejection systems than applying either approach singularly. Ultimately this research will have the potential to improve decision making during acquisition, decrease disputes during acquisition, and increase the lethality and capability of our pilots in combat, by giving development teams an accurate set of constraints for when they test HMDs and ejection systems. Enabling the best capability to be given to the pilot, while also keeping them safe in the event they need to eject provides a method to facilitate system Human Systems Integration tradeoffs.

Recommendations for Future Research

The first recommendation for future research would be to acquire better injurious data for the x and y acceleration directions. Currently for the x direction, only the peak load and moment values for the terms used for the Nij are available to support analysis. For the y direction, there is only time histories for the terms used for the Nij criterion. Therefore, the analysis would be greatly improved if full six degrees of freedom and time histories were available for x and y injurious data. Additionally, there is no satisfactory data available for the z direction. Collection of this data would significantly improve the capability to derive more reliable MANIC values.

The second recommendation is to combine all three axes together for MANIC calculations, then apply an optimization as illustrated in this thesis. This analysis will show if it is possible to develop the MANIC into something that can be used on multidirectional acceleration event like an ejection. This analysis will optimize the critical values to provide easily communicated cutoff values for evaluation for the three directions. If successful, this will provide an easily communicated criteria for escape system evaluation.

The final recommendation, to be done after a successful completion of the second recommendation, is to develop a transform function for applying the MANIC to ATD data. Currently, full ejection tests are performed with ATDs and not humans due to risk. Due to the difficulty of building a truly bio-fidelic crash dummy, the ATDs do not respond to accelerations in the same way as humans. Therefore, something is needed to transfer the data from a test done with ATDs into an accurate representation of a human response. This would be the final step in developing a tool to completely and accurately evaluate ejection-based escape systems for high-performance aircraft.

Appendix A: Data Origins

Loading Orientation, Facility, Cell, and Test Number Tables

X Direction Data

Facility: HIA

Cell	Test Numbers	Cell	Test Numbers	Cell	Test Numbers	Cell	Test Numbers
B	7327	C	7364	D	7422	PMHS	3022
	7341		7367		7423		3026
	7342		7368		7425		3032
	7351		7381		7435		3035
	7360		7405		7439		3038
	7361		7406		7443		3039
	7365		7411		7447		
	7366		7412		7450		
	7369		7418		7451		
	7373		7419		7453		
	7374		7420		7454		
	7377		7427		7458		
	7378		7428		7459		
	7380		7430		7461		
	7382		7432		7462		
	7402		7433		7471		
	7403		7445		7482		
	7407		7449		7483		
	7409		7457		7497		
	7415		7467		7711		
	7416		7625		7717		
	7424		7673		7723		
	7436		7678		7758		
	7437		7679				
	7507		7705				
	7637		7746				
	7655						

Y Direction Data

Facility: **HIA**

Cell	Test Numbers	Cell	Test Numbers	Cell	Test Numbers
C	6750	F	6881	PMHS	1
	6751		6882		2
	6752		6885		3
	6753		6892		4
	6755		6893		5
	6757		6894		6
	6758		6895		7
	6759		6899		8
	6760		6900		9
	6761		6905		
	6762		6906		
	6769		6907		
	6770		6909		
	6771		6910		
	6772		6913		
	6773		6915		
	6774		6916		
	6775		6917		
	6781		6918		
	6782		6919		
	6783		6926		
	6806		6927		
	6807		6929		
	6809				
	6810				
	6820				
	6821				
	6822				
	6833				
	6834				

Appendix B: Matlab Code

This Appendix contains all of the Matlab codes used for this research. They are presented in alphabetical order. The file names are bulleted, then followed by the code. Some of them have file directories that would need to be changed if ran on a different computer to access the data spreadsheets. The two main ones are SetupOptimization5 and PlotSurvivalAnalysis3. SetupOptimization5 will find the values for the optimization parameters, and the different optimization scenarios can be adjusted by changing the array for “x”. PlotSurvivalAnalysis3 plots the survival analysis curves, and if the optimization parameters entered, can plot the different scenarios by commenting in/out the different parameter arrays.

adjfits3

```
function [parameters] = adjfits3(fits, xSelect, paramadj)
%formatfits simply copies the slopes and intercepts out of fits and
%populates parameters with the appropriate values.
% INPUT
% fits is the fit functions for Fx, Fz, nFz, Mz and My
% xSelect indicates pairings of values to be fit
% OUTPUT
% parameters - slope and intercept parameters for Fx, Fz, nFz,
numfits = length(paramadj);
for i=1:numfits
   [~,cols,~] = find(xSelect==i);
   for j=1:length(cols)
      if (cols(j) == 1)
         parameters.pos.Fx.slope = paramadj(1,i) .* fits.Fx.p1;
         parameters.pos.Fx.int = paramadj(1,i) .* fits.Fx.p2;
         parameters.neg.Fx.slope = paramadj(1,i) .* fits.Fx.p1;
         parameters.neg.Fx.int = paramadj(1,i) .* fits.Fx.p2;
      elseif(cols(j) == 2)
         parameters.pos.Fy.slope = paramadj(1,i) .* fits.Fx.p1;
         parameters.pos.Fy.int = paramadj(1,i) .* fits.Fx.p2;
         parameters.neg.Fy.slope = paramadj(1,i) .* fits.Fx.p1;
         parameters.neg.Fy.int = paramadj(1,i) .* fits.Fx.p2;
      elseif(cols(j) == 3)
         parameters.pos.Fz.slope = paramadj(1,i) .* fits.Fz.p1;
         parameters.pos.Fz.int = paramadj(1,i) .* fits.Fz.p2;
         parameters.neg.Fz.slope = paramadj(1,i) .* fits.nFz.p1;
         parameters.neg.Fz.int = paramadj(1,i) .* fits.nFz.p2;
      elseif(cols(j) == 4)
         % Moment Fits
         parameters.pos.Mx.slope = paramadj(1,i) .* fits.Mx.p1;
         parameters.pos.Mx.int = paramadj(1,i) .* fits.Mx.p2;
         parameters.neg.Mx.slope = paramadj(1,i) .* fits.Mx.p1;
         parameters.neg.Mx.int = paramadj(1,i) .* fits.Mx.p2;
      elseif(cols(j) == 5)
         parameters.pos.My.slope = paramadj(1,i) .* fits.My.p1;
         parameters.pos.My.int = paramadj(1,i) .* fits.My.p2;
         parameters.neg.My.slope = paramadj(1,i) .* fits.Mx.p1;
         parameters.neg.My.int = paramadj(1,i) .* fits.Mx.p2;
      elseif(cols(j) == 6)
         parameters.pos.Mz.slope = paramadj(1,i) .* fits.Mx.p1;
         parameters.pos.Mz.int = paramadj(1,i) .* fits.Mx.p2;
         parameters.neg.Mz.slope = paramadj(1,i) .* fits.Mx.p1;
         parameters.neg.Mz.int = paramadj(1,i) .* fits.Mx.p2;
      else
```

```
      end
    end
  end
end
```

ComputeSurvivalAnalysis

```
% Routine to calculate Survival Functions
clear all;
close all;
clc;

path = 'C:\Users\Ethan\Documents\MATLAB\Survival Analysis Optimization\Gy Excel Data'; % Directory which contains
excel files
filenames = dir([path,'\*.xlsx']);

%% STEP 2: Read Data
loading = readLoading(filenames);        % Raw neck loading time history with participant Mass

%% STEP 3: Calculate MANIC Values
% Obtain fitting parameters for critical values
metric = false;
[fits, goodness] = fitfunctions(metric);
[parameters] = formatfits(fits);
% Perform manic calculation for each participant/condition
setf = 0;
for i=1:size(loading,1)
    [manic(i,1), manicIndex(i,1), NMIx(i,1), NMIxindex(i,1)] = paramMANIC(loading(i).Mass, loading(i), parameters);
    loading(i).manic=manic(i,1);
    if(loading(i).injured == 0)
        survinput(i,:) = [manic(i,1), inf];
    else
        survinput(i,:) = [0, manic(i,1)];
%       if(manic(i,1) >0.9)&&(manic(i,1)< 1.0) && (setf == 0)
%           setf = 1;
%           survinput(i,1) = manic(i,1);
%       end
    end
end


%% Step 4: Write Data

% for i=1:size(loading,1)
%     carray{i,1} = filenames(i).name;
%     carray{i,2} = loading(i).Mass;
%     carray{i,3} = loading(i).HeadCircumference;
%     carray{i,4} = loading(i).HeadMass;
%     carray{i,5} = manic(i,1);
%     carray{i,6} = manicIndex(i,1);
%     carray{i,7} = NMIx(i,1);
%     carray{i,8} = NMIxindex(i,1);
% end
% outfile = '\\DISKSTATION\Work Files\Research\Ethan\Ethans Analysis\newoutput.xls';
% xlswrite(outfile, carray);
%% STEP 4: Perform Survival Analysis
options=optimset('MaxFunEvals',10000,'MaxIter',10000); %do the same by also providing some option to fminsearchbnd
since minimizer=1
% [A, B]=wblfit(survinput,1,[2 2],options)
[pars covars SE gval exitflag]=logistfitc(survinput,1,[2 2],options);

%% STEP 5: Plot Survival Functions
```

```
x=zeros(length(loading),1);
y=zeros(length(loading), 1);
for i=1:length(loading)
   x(i) = loading(i).manic;
   y(i) = loading(i).injured;
end
plot(x, y, 'ks');
hold on
X = 0:.01:max(x);
curve = 1./(1+exp(-(X-pars(1))./(pars(2))));
plot(X, curve, 'k-');
```

critValues

```
function [critFx, critFy, critFz, critMx, critMy, critMz] = critValues(mass,parameters)
%UNTITLED Summary of this function goes here
%   Detailed explanation goes here

%INPUTS:
% mass - the mass of the human or ATD given as a single value.
% parameters - parameters to linear equations for the critical values
%
% OUTPUTS:

%
% Routine written by Michael E. Miller November 20, 2020

%% Check Inputs
if nargin < 2
   error('Not enough parameters input to paramManic');
end


%% STEP 1: Determine Critical Values

% Determine critical values for Fx
critFx.p = parameters.pos.Fx.int +parameters.pos.Fx.slope.*mass;
critFx.n = parameters.neg.Fx.int + parameters.neg.Fx.slope.*mass;

% Determine critical values for Fy
critFy.p = parameters.pos.Fy.int + parameters.pos.Fx.slope.*mass;
critFy.n = parameters.neg.Fy.int + parameters.neg.Fy.slope.*mass;

% Determine critical values for Fz
critFz.p = parameters.pos.Fz.int + parameters.pos.Fz.slope.*mass;
critFz.n = parameters.neg.Fz.int + parameters.neg.Fz.slope.*mass;

% Determine critical values for Mx
critMx.p = parameters.pos.Mx.int + parameters.pos.Mx.slope .* mass;
critMx.n = parameters.neg.Mx.int + parameters.neg.Mx.slope .* mass;

% Determine critical values for My
critMy.p = parameters.pos.My.int + parameters.pos.My.slope .* mass;
critMy.n = parameters.neg.My.int + parameters.neg.My.slope .* mass;

% Determine critical values for Mz
critMz.p = parameters.pos.Mz.int + parameters.pos.Mz.slope .* mass;
critMz.n = parameters.neg.Mz.int + parameters.neg.Mz.slope .* mass;

end
```

- defaultMANIC

```
function varargout = defaultMANIC(mass, load, metric)
%MANIC The purpose of this function is to calculate the MANIC value given the
% values input.
%
%INPUTS:
% mass - the mass of the human or ATD given as a single value.
% load - a structure assumed to contain Fx, Fy, Fz, Mx, My and Mz as arrays
%        of values captured throughout the run.
% metric is an optional variable boolean, assumed to be true but can be set
%        to false if the mass and load is input in english units
%
% OUTPUTS:
% manic - maximum manic value
% manicindex - optional index to the load producing the maximum manic value
% NMIx - neck moment index about the x axis
% NMIxindex - optional index to the load producing the maximum NIMIx
%
% Routine written by Michael E. Miller June 4, 2020

%% Check Inputs
if nargin < 3
   metric = true;
end
if nargin < 2
   error('Mass and load must be input to the function MANIC');
end

%% STEP 1: Setup MANIC Critical Values
[massVals, crit] = getCriticalValues;
%% STEP 2: Determine correct critical value and units
if(metric)
   unit = 2;
else
   unit=1;
end
vals = find(massVals.Human(:,unit) < mass);
critVal = size(vals,1);


%% STEP 3: Set up arrays containing proper critical values
lengthArray = size(load.Fx,1);

% Determine critical values for Fx
critFx = repmat(crit.nFx(critVal, unit), lengthArray, 1);
xindex = find(load.Fx >=0);
critFx(xindex) = repmat(crit.Fx(critVal, unit), size(xindex,1), 1);

% Determine critical values for Fy
critFy = repmat(crit.nFy(critVal, unit), lengthArray, 1);
xindex = find(load.Fx >=0);
critFy(xindex) = repmat(crit.Fy(critVal, unit), size(xindex,1), 1);

% Determine critical values for Fz
critFz = repmat(crit.nFz(critVal, unit), lengthArray, 1);
xindex = find(load.Fz >=0);
critFz(xindex) = repmat(crit.Fz(critVal, unit), size(xindex,1), 1);

% Determine critical values for Fz
critMx = repmat(crit.nMx(critVal, unit), lengthArray, 1);
xindex = find(load.Mx >=0);
critMx(xindex) = repmat(crit.Mx(critVal, unit), size(xindex,1), 1);

% Determine critical values for Fz
critMy = repmat(crit.nMy(critVal, unit), lengthArray, 1);
```

```
xindex = find(load.Fz >=0);
critMy(xindex) = repmat(crit.My(critVal, unit), size(xindex,1), 1);

% Determine critical values for Fz
critMz = repmat(crit.nMz(critVal, unit), lengthArray, 1);
xindex = find(load.Mz >=0);
critMz(xindex) = repmat(crit.Mz(critVal, unit), size(xindex,1), 1);

%% STEP 4: Calculate MANIC

manicArray = sqrt((load.Fx./critFx).^2 + (load.Fy ./ critFy).^2 + ...
        (load.Fz ./ critFz).^2 + (load.Mx ./ critMx).^2 + ...
        (load.My ./ critMy).^2 + (load.Mz ./ critMz).^2);
[manic, mindex] = max(manicArray(:,1));

%% STEP 5: Calculate NMIx

[MxPeak, NMIxindex] = max(abs(load.Mx));
NMIx = MxPeak./critMx(1,1);

%% Output Appropriate Variables

if(nargout == 1)
   varargout = {manic};
elseif(nargout == 2)
   varargout = {manic, mindex};
elseif(nargout ==3)
   varargout = {manic, mindex, NMIx};
else
   varargout = {manic, mindex, NMIx, NMIxindex};
end

end
```

fitfunctions

```
function [fits, goodness] = fitfunctions(metric)
%fitfunctions - fit functions to the critical value axes

if(metric)      % Select data column based on English (col 1) or metric (col 2)
   col = 2;
else
   col=1;
end


[massVals, crit] = getCriticalValues();
[fits.Fx, goodness.Fx] = fit(massVals.ATD(:,col), crit.Fx(:,col), 'poly1');
[fits.Fz, goodness.Fz] = fit(massVals.ATD(:,col), crit.Fz(:,col), 'poly1');
[fits.nFz, goodness.nFz]=fit(massVals.ATD(:,col), crit.nFz(:,col), 'poly1');
[fits.Mx, goodness.Mz] = fit(massVals.ATD(:,col), crit.Mx(:,col), 'poly1');
[fits.My, goodness.My] = fit(massVals.ATD(:,col), crit.My(:,col), 'poly1');

end
```

format fits

```
function [parameters] = formatfits(fits)
%formatfits simply copies the slopes and intercepts out of fits and
%populates parameters with the appropriate values.
```

```
% INPUT
% fits is the fit functions for Fx, Fz, nFz, Mz and My
% OUTPUT
% parameters - slope and intercept parameters for Fx, Fz, nFz,


parameters.pos.Fx.slope = fits.Fx.p1;
parameters.pos.Fx.int = fits.Fx.p2;
parameters.neg.Fx.slope = fits.Fx.p1;
parameters.neg.Fx.int = fits.Fx.p2;

parameters.pos.Fy.slope = fits.Fx.p1;
parameters.pos.Fy.int = fits.Fx.p2;
parameters.neg.Fy.slope = fits.Fx.p1;
parameters.neg.Fy.int = fits.Fx.p2;

parameters.pos.Fz.slope = fits.Fz.p1;
parameters.pos.Fz.int = fits.Fz.p2;
parameters.neg.Fz.slope = fits.nFz.p1;
parameters.neg.Fz.int = fits.nFz.p2;

% Moment Fits
parameters.pos.Mx.slope = fits.Mx.p1;
parameters.pos.Mx.int = fits.Mx.p2;
parameters.neg.Mx.slope = fits.Mx.p1;
parameters.neg.Mx.int = fits.Mx.p2;

parameters.pos.My.slope = fits.My.p1;
parameters.pos.My.int = fits.My.p2;
parameters.neg.My.slope = fits.Mx.p1;
parameters.neg.My.int = fits.Mx.p2;

parameters.pos.Mz.slope = fits.Mx.p1;
parameters.pos.Mz.int = fits.Mx.p2;
parameters.neg.Mz.slope = fits.Mx.p1;
parameters.neg.Mz.int = fits.Mx.p2;

end
```

getCriticalValues

```
function [massVals, crit] = getCriticalValues()
% getCriticalValues returns standard mass values and corresponding critical
% values.
% INPUTS
% null
% OUTPUTS
% massVals - mass values of the ATDs or lower bound for humans
% crit - critical values
%
% Critical Values Taken From:
% Parr, J.C. Miller, M.E., Colombi, J.M., Schubert Kabban, C.M. and
% Pellettiere, J.A. (2015) Development of a Side-Impact (Gy) Neick Injury
% Criterion for Use in Aircraft and Vehicle Safety Evaluation, IIE
% Transactions on Occupational Ergonomics and Human Factors, 3:3-4,
% 151-164.

% ATD Mass in Each Category (lb, kg)
massVals.ATD = [46.7; 56.7; 61.7; 68.0; 78.0; 90.7; 99.8; 111.1];
massVals.ATD(:,2) = massVals.ATD(:,1);
massVals.ATD(:,1) = 2.20462.*massVals.ATD(:,1);
```

```
% Minimum Human Mass in Each Category (lb kg)
massVals.Human = [0; 51.7; 59.2; 64.9; 73.0; 84.4; 95.3; 105.5];
massVals.Human(:,2) = massVals.Human(:,1);
massVals.Human(:,1) = 2.20462.*massVals.Human(:,1);

% Critical Force Values for Each Mass Cateogry (lb, N)
crit.Fx = [405, 1802; 496, 2206; 522, 2322; 561, 2495; 625, 2780; ...
        683, 3038; 777, 3456; 836, 3719];
crit.nFx = crit.Fx;
crit.Fy = crit.Fx;
crit.nFy = crit.Fx;
crit.Fz = [964, 4287; 1214, 5400; 1278, 5685; 1373, 6107; 1530, 6806; ...
        1671, 7433; 1847, 8216; 2047, 9106];
crit.nFz = [872, 3880; 1099, 4889; 1157, 5147; 1243, 5529; 1385, 6160; ...
        1513, 6730; 1673, 7440; 1853, 8243];
% Critical Moment Values for each Mass Category (in-lb, Nm)
crit.Mx = [593, 67; 845, 95; 912, 103; 1016, 115; 1195, 135; ...
        1364, 154; 1584, 179; 1850, 209];
crit.nMx = crit.Mx;
crit.nMy = crit.Mx;
crit.Mz = crit.Mx;
crit.nMz = crit.Mx;
crit.My = [1373, 155; 1939, 210; 2094, 237; 2333, 264; 2744, 310; ...
        3133, 354; 3673, 415; 4248, 480];

end
```

MANIC

```
function varargout = defaultMANIC(mass, load, metric)
%MANIC The purpose of this function is to calculate the MANIC value given the
% values input.
%
%INPUTS:
% mass - the mass of the human or ATD given as a single value.
% load - a structure assumed to contain Fx, Fy, Fz, Mx, My and Mz as arrays
%       of values captured throughout the run.
% metric is an optional variable boolean, assumed to be true but can be set
%       to false if the mass and load is input in english units
%
% OUTPUTS:
% manic - maximum manic value
% manicindex - optional index to the load producing the maximum manic value
% NMIx - neck moment index about the x axis
% NMIxindex - optional index to the load producing the maximum NIMIx
%
% Routine written by Michael E. Miller June 4, 2020

%% Check Inputs
if nargin < 3
  metric = true;
end
if nargin < 2
  error('Mass and load must be input to the function MANIC');
end

%% STEP 1: Setup MANIC Critical Values
[massVals, crit] = getCriticalValues(metric);
%% STEP 2: Determine correct critical value and units
if(metric)
  unit = 1;
else
```

```
    unit=0;
    massVals.Human = 2.20462.*massVals.Human; % Convert mass of human to kg
end
vals = find(massVals.Human < mass);
critVal = size(vals,1) + 1;


%% STEP 3: Set up arrays containing proper critical values
lengthArray = size(load.Fx,1);

% Determine critical values for Fx
critFx = repmat(crit.nFx(critVal, unit), lengthArray, 1);
xindex = find(load.Fx >=0);
critFx(xindex) = repmat(crit.Fx(critVal, unit), size(xindex,1), 1);

% Determine critical values for Fy
critFy = repmat(crit.nFy(critVal, unit), lengthArray, 1);
xindex = find(load.Fx >=0);
critFy(xindex) = repmat(crit.Fy(critVal, unit), size(xindex,1), 1);

% Determine critical values for Fz
critFz = repmat(crit.nFz(critVal, unit), lengthArray, 1);
xindex = find(load.Fz >=0);
critFz(xindex) = repmat(crit.Fz(critVal, unit), size(xindex,1), 1);

% Determine critical values for Fz
critMx = repmat(crit.nMx(critVal, unit), lengthArray, 1);
xindex = find(load.Mx >=0);
critMx(xindex) = repmat(crit.Mx(critVal, unit), size(xindex,1), 1);

% Determine critical values for Fz
critMy = repmat(crit.nMy(critVal, unit), lengthArray, 1);
xindex = find(load.Fz >=0);
critMy(xindex) = repmat(crit.My(critVal, unit), size(xindex,1), 1);

% Determine critical values for Fz
critMz = repmat(crit.nMz(critVal, unit), lengthArray, 1);
xindex = find(load.Mz >=0);
critMz(xindex) = repmat(crit.Mz(critVal, unit), size(xindex,1), 1);

%% STEP 4: Calculate MANIC

manicArray = sqrt((load.Fx./critFx).^2 + (load.Fy ./ critFy).^2 + ...
        (load.Fz ./ critFz).^2 + (load.Mx ./ critMx).^2 + ...
        (load.My ./ critMy).^2 + (load.Mz ./ critMz).^2);
[manic, mindex] = max(manicArray(:,1));

%% STEP 5: Calculate NMIx

[MxPeak, NMIxindex] = max(abs(load.Mx));
NMIx = MxPeak./critMx(1,1);

%% Output Appropriate Variables

if(nargout == 1)
    varargout = {manic};
elseif(nargout == 2)
    varargout = {manic, mindex};
elseif(nargout ==3)
    varargout = {manic, mindex, NMIx};
else
    varargout = {manic, mindex, NMIx, NMIxindex};
end
```

```
end
```

MANIC_CritValEqu

```
function varargout = MANIC_CritValEqu(mass, load, parameters)
%MANIC The purpose of this function is to calculate the MANIC value given the
% values input.  It relies on linear parameters to determine critical
% values
%
%INPUTS:
% mass - the mass of the human or ATD given as a single value.
% load - a structure assumed to contain Fx, Fy, Fz, Mx, My and Mz as arrays
%         of values captured throughout the run.
% parameters - linear slopes and offsets for each axis, corresponding to
% the critical values
%
% OUTPUTS:
% manic - maximum manic value
% manicindex - optional index to the load producing the maximum manic value
% NMIx - neck moment index about the x axis
% NMIxindex - optional index to the load producing the maximum NIMIx
%
% Routine written by Michael E. Miller June 4, 2020



%% STEP 1: Calculate Critical Values from Parameters and Mass
critFx = parameters.pos.Fx.slope.*mass + parameters.pos.Fx.int;
critFx = critFx *ones(size(load.Fx,1),1);
critnFx = parameters.neg.Fx.slope.*mass + parameters.neg.Fx.int;
critFx = critnFx(find(load.Fx(:,1) < 0), 1);

critFy = parameters.pos.Fy.slope.*mass + parameters.pos.Fy.int;
critFy = critFy *ones(size(load.Fx,1),1);
critnFy = parameters.neg.Fy.slope.*mass + parameters.neg.Fy.int;
critFy = critnFy(find(load.Fy(:,1) < 0), 1);

critFz = parameters.pos.Fz.slope.*mass + parameters.pos.Fz.int;
critFz = critFz *ones(size(load.Fx,1),1);
critnFz = parameters.neg.Fz.slope.*mass + parameters.neg.Fz.int;
critFz = critnFz(find(load.Fz(:,1) < 0), 1);

% Moment calculatons
critMx = parameters.pos.Mx.slope.*mass + parameters.pos.Mx.int;
critMx = critMx *ones(size(load.Fx,1),1);
critnMx = parameters.neg.Mx.slope.*mass + parameters.neg.Mx.int;
critMx = critnMx(find(load.Mx(:,1) < 0), 1);

critMy = parameters.pos.My.slope.*mass + parameters.pos.My.int;
critMy = critMy *ones(size(load.Fx,1),1);
critnMy = parameters.neg.My.slope.*mass + parameters.neg.My.int;
critMy = critnmMy(find(load.My(:,1) < 0), 1);

critMz = parameters.pos.Mz.slope.*mass + parameters.pos.Mz.int;
critMz = critMz *ones(size(load.Fx,1),1);
critnMz = parameters.neg.Mz.slope.*mass + parameters.neg.Mz.int;
critMz = critnMz(find(load.Mz(:,1) < 0), 1);

%% STEP 2: Calculate MANIC

manicArray = sqrt((load.Fx./critFx).^2 + (load.Fy ./ critFy).^2 + ...
        (load.Fz ./ critFz).^2 + (load.Mx ./ critMx).^2 + ...
        (load.My ./ critMy).^2 + (load.Mz ./ critMz).^2);
[manic, mindex] = max(manicArray(:,1));
```

```
%% STEP 5: Calculate NMIx

[MxPeak, NMIxindex] = max(abs(load.Mx));
NMIx = MxPeak./critMx(1,1);

%% Output Appropriate Variables

if(nargout == 1)
   varargout = {manic};
elseif(nargout == 2)
   varargout = {manic, mindex};
elseif(nargout ==3)
   varargout = {manic, mindex, NMIx};
else
   varargout = {manic, mindex, NMIx, NMIxindex};
end

end
```

Opt3

```
function [diffAim] = Opt3(paramadj)
%Opt1 is a routine for performing an initial optimization.  All it does is
% permit the slopes and intercepts to be adjusted by a factor and calculate
% the probability for a MANIC equal to 1
%
% INPUTS
% loading - data needed for manic and survivability analyis
% fits - the slope and intercept values for the functions fit to critical
% values
% paramadj - the adjustments made to the parameters of the fits
% plot - boolean indicating whether the survivability function should be
% plotted
%
% OUTPUTS
% diffAim The difference in proprotion of 0.05 with a MANIC value equal to 1.
load('workdata');
[parameters] = adjfits3(fits, xSelect, paramadj); % Adjust parameters based on paramadj
                                                  % Calculate Manic
for i=1:size(loading,1)
   [manic(i,1), manicIndex(i,1), NMIx(i,1), NMIxindex(i,1)] = paramMANIC(loading(i).Mass, loading(i), parameters);
   loading(i).manic=manic(i,1);
   if(loading(i).injured == 0)
      survinput(i,:) = [manic(i,1), inf];
   else
      survinput(i,:) = [0, manic(i,1)];
%       if(manic(i,1) >0.9)&&(manic(i,1)< 1.0) && (setf == 0)
%          setf = 1;
%          survinput(i,1) = manic(i,1);
%       end
   end
end
```

- OptimizationScript

```
clear all
close all

path = '\\diskstation\work files\Research\Ethan\Applying Justin Williams Data\ExcelData';                    %
Directory which contains excel files
filenames = dir([path,'\*.xlsx']);
loading = readLoading(filenames);                     % Raw neck loading time history
```

```
metric=1;
[fits, goodness] = fitfunctions(metric); % Fit equations to Critical Values
parameters = formatfits(fits);           % Format the fits into parameters
% need mass
[manic, mindex, NMIx, NMIxindex] = paramMANIC(mass, load, parameters);
```

paramMANIC

```
function varargout = paramMANIC(mass, load, parameters)
%MANIC The purpose of this function is to calculate the MANIC value given the
% values and the parameters input.
%
%INPUTS:
% mass - the mass of the human or ATD given as a single value.
% load - a structure assumed to contain Fx, Fy, Fz, Mx, My and Mz as arrays
%        of values captured throughout the run.
% parameters - parameters to linear equations for the critical values
%
% OUTPUTS:
% manic - maximum manic value
% manicindex - optional index to the load producing the maximum manic value
% NMIx - neck moment index about the x axis
% NMIxindex - optional index to the load producing the maximum NIMIx
%
% Routine written by Michael E. Miller August 24, 2020

%% Check Inputs
if nargin < 3
   error('Not enough parameters input to paramManic');
end


%% STEP 1: Determine Critical Values

loadsize = length(load.Fx);

% Determine critical values for Fx
critFx = repmat(parameters.pos.Fx.int +parameters.pos.Fx.slope.*mass, loadsize,1);
xindex = find(load.Fx <0);
if(xindex ~=0)
   critFx(xindex) = repmat(parameters.neg.Fx.int + parameters.neg.Fx.slope.*mass, length(xindex),1);
end

% Determine critical values for Fy
critFy = repmat(parameters.pos.Fy.int + parameters.pos.Fx.slope.*mass, loadsize,1);
yindex = find(load.Fy < 0);
if(yindex ~=0)
   critFy(yindex) = repmat(parameters.neg.Fy.int + parameters.neg.Fy.slope.*mass, length(yindex), 1);
end

% Determine critical values for Fz
critFz = repmat(parameters.pos.Fz.int + parameters.pos.Fz.slope.*mass, loadsize,1);
zindex = find(load.Fz < 0);
if(zindex ~=0)
   critFz(zindex) = repmat(parameters.neg.Fz.int + parameters.neg.Fz.slope.*mass, length(zindex), 1);
end

% Determine critical values for Mx
critMx = repmat(parameters.pos.Mx.int + parameters.pos.Mx.slope .* mass, loadsize, 1);
xMindex = find(load.Mx < 0);
if(xMindex ~=0)
   critMx(xMindex) = repmat(parameters.neg.Mx.int + parameters.neg.Mx.slope .* mass, length(xMindex), 1);
end
```

```
% Determine critical values for My
critMy = repmat(parameters.pos.My.int + parameters.pos.My.slope .* mass, loadsize,1);
yMindex = find(load.My < 0);
if(yMindex ~= 0)
   critMy(yMindex) = repmat(parameters.neg.My.int + parameters.neg.My.slope .*mass, length(yMindex), 1);
end

% Determine critical values for Mz
critMz = repmat(parameters.pos.Mz.int + parameters.pos.Mz.slope .* mass, loadsize,1);
zMindex = find(load.Mz < 0);
if(zMindex ~= 0)
   critMz(zMindex) = repmat(parameters.neg.Mz.int + parameters.neg.Mz.slope .* mass, length(zMindex), 1);
end

%% STEP 4: Calculate MANIC

manicArray = sqrt((load.Fx./critFx).^2 + (load.Fy ./ critFy).^2 + ...
         (load.Fz ./ critFz).^2 + (load.Mx ./ critMx).^2 + ...
         (load.My ./ critMy).^2 + (load.Mz ./ critMz).^2);

[manic, mindex] = max(manicArray(:,1));

%% STEP 5: Calculate NMIx

[MxPeak, NMIndex] = max(abs(load.Mx));
if(load.Mx(NMIndex) >=0)
   critMx = parameters.pos.Mx.int +parameters.pos.Mx.slope.*mass;
else
   critMx = parameters.neg.Mx.int + parameters.neg.Mx.slope.*mass;
end
NMIx = MxPeak./critMx;

%% Output Appropriate Variables

if(nargout == 1)
   varargout = {manic};
elseif(nargout == 2)
   varargout = {manic, mindex};
elseif(nargout ==3)
   varargout = {manic, mindex, NMIx};
else
   varargout = {manic, mindex, NMIx, NMIndex};
end

end
```

PlotSurvivalAnalysis

```
% Routine to calculate Survival Functions
clear all;
%close all;
clc;

DataSets = [0; 1; 0];  % Data sets to be read, 1, indicates include this set in the analysis, [x; y; z];
Xloading = [];
Yloading = [];
Zloading = [];
filenames = [];
linfits = true;
if(DataSets(1)==1)
```

```
    path = 'C:\Users\Ethan\Documents\MATLAB\Survival Analysis Optimization\Gx Excel Data'; % Directory which contains
Gx excel files
    filenames = dir([path,'\*.xlsx']);
    %% STEP 2: Read Data
    Xloading = readXLoading(filenames);         % Raw neck loading time history with participant Mass
end
numXvals = size(filenames,1);
filenames = [];
if(DataSets(2))
    path = 'C:\Users\Ethan\Documents\MATLAB\Survival Analysis Optimization\Gy Excel Data';
    %path = '\\diskstation\work files\Research\Ethan\Applying Justin Williams Data\ExcelData\';           % Directory which
contains Gy excel files
    filenames = dir([path,'\*.xlsx']);

    %% STEP 2: Read Data
    Yloading = readYLoading(filenames);         % Raw neck loading time history with participant Mass
end
numYvals = size(filenames,1);
filenames = [];
if(DataSets(3))
    path = 'C:\Users\Ethan\Documents\MATLAB\Survival Analysis Optimization\Gz Excel Data'; % Directory which contains
Gx excel files
    filenames = dir([path,'\*.xlsx']);
end
numZvals = size(filenames,1);
loading = [Xloading; Yloading; Zloading];

%% STEP 3: Calculate MANIC Values
% Obtain fitting parameters for critical values
metric = false;
[fits, goodness] = fitfunctions(metric);
[parameters] = formatfits(fits);

%% Change both xSelect and x values
xSelect = [1 2 3 4 5 6];
 x = [1.0 1.0 1.0 1.0 1.0 1.0];
% x = [0.6598  0.6598  0.6598  0.6598  0.6598  0.6598];
% x = [1.1124  1.1124  1.1124  0.5132  0.5132  0.5132];
% x = [0.9286  0.9611  1.1468  0.3766  1.0174  1.2251];
% Just optimizing X
% x = [];
% Just optimizing Y
% x = [];

[parameters] = adjfits3(fits, xSelect, x); % Adjust parameters based on paramadj
setf = 0;
for i=1:size(loading,1)
    if(linfits)
        [manic(i,1), manicIndex(i,1), NMIx(i,1), NMIxindex(i,1)] = paramMANIC(loading(i).Mass, loading(i), parameters);
    else
        [manic(i,1), manicIndex(i,1), NMIx(i,1), NMIxindex(i,1)] = defaultMANIC(loading(i).Mass, loading(i), metric);
    end
    loading(i).manic=manic(i,1);
    mass(i) = loading(i).Mass;
    if(loading(i).injured == 0)
        survinput(i,:) = [manic(i,1), inf];
    else
        survinput(i,:) = [0, manic(i,1)];
%         if(manic(i,1) >0.9)&&(manic(i,1)< 1.0) && (setf == 0)
%             setf = 1;
%             survinput(i,1) = manic(i,1);
%         end
    end
end
```

```
xlswrite('myoutput.xls', [mass' manic]);

%% STEP 4: Perform Survival Analysis
options=optimset('MaxFunEvals',10000,'MaxIter',10000); %do the same by also providing some option to fminsearchbnd
since minimizer=1
% [A, B]=wblfit(survinput,1,[2 2],options)
[pars covars SE gval exitflag]=logistfitc(survinput,1,[2 2],options);

%% STEP 5: Plot Survival Functions
x=zeros(length(loading),1);
y=zeros(length(loading), 1);
for i=1:length(loading)
   x(i) = loading(i).manic;
   y(i) = loading(i).injured;
end
figure;
plot(x(1:numXvals), 100.*y(1:numXvals), 'ks');
hold on
if(numYvals ~= 0)
   plot(x((numXvals+1):(numXvals+numYvals)), 100.*y((numXvals+1):(numXvals+numYvals)), 'bd');
end
X = 0:.001:max(x);
curve = 1./(1+exp(-(X-pars(1))./(pars(2))));
plot(X, 100.*curve, 'k-');
xlabel('MANIC');
ylabel('Probability of Injury');
% Inverse Logistic Function
val = 1.0;      % This is the manic valuefor which the probability is calculated.
probManic = 1./(1+exp(-(val-pars(1))./(pars(2))))
pM = 0.05;
val=pars(1) -(pars(2)).*log((1./pM)-1);
```

readLoading

```
function [loading] = readLoading(filenames)
% Written by: Michael Miller & Justin Williams
% Date: 05/22/2018
%
% INPUTS: 1, Path to Excel Files
%         2, List of Filenames
%
% This code reads the files provided to it and sorts the data into its
% individual components.
%
% OUTPUTS: 1, Raw Neck Loading
%% Define Location of Fx, Fy, Fz, Mx, My, Mz by column number
loc = [2, 3, 4, 5, 6, 7];
startrow = 2;   % Define the starting row in the data file

[mass] = xlsread('C:\Users\Ethan\Documents\MATLAB\Survival Analysis Optimization\Gy_test Numbers and
Weights.xlsx', 'Sheet1', 'B2:D66');
loadstruct = struct( ...
      'injured', false, ...
      'Mass', 0, ...
      'Fx', 0, ...
      'Fy', 0, ...
      'Fz', 0, ...
      'Mx', 0, ...
      'My', 0, ...
      'Mz', 0 ...
      );
loading = repmat(loadstruct, size(filenames,1), 1);
```

```
for i = 1:length(filenames)
   curfile = [filenames(i).folder '\' filenames(i).name];
%    if(strcmp(filenames(i).name(1,1:4),'PMHS'))
%        loading(i).injured = true;
%    end
   [num,~,~] = xlsread(curfile, 'Time History');

   if(strcmp(filenames(i).name(1:4),'PMHS'))
      fnumber = str2double(filenames(i).name(1,5));
   else
      fnumber = str2double(filenames(i).name(1,1:4));
   end
   [j,~]=find(mass(:,1)==fnumber);
   loading(i).Mass=mass(j,2);
   loading(i).injured = mass(j,3);


   loading(i).Fx = num(startrow:end,loc(1));
   loading(i).Fy = num(startrow:end,loc(2));
   loading(i).Fz = num(startrow:end,loc(3));
   loading(i).Mx = num(startrow:end,loc(4));
   loading(i).My = num(startrow:end,loc(5));
   loading(i).Mz = num(startrow:end,loc(6));
end
```

readXLoading

```
function [loading] = readXLoading(filenames)
% Written by: Michael Miller & Justin Williams
% Date: 05/22/2018
%
% INPUTS: 1, Path to Excel Files
%        2, List of Filenames
%
% This code reads the files provided to it and sorts the data into its
% individual components.
%
% OUTPUTS: 1, Raw Neck Loading
%% Define Location of Fx, Fy, Fz, Mx, My, Mz by column number
loc = [2, 0, 4, 0, 3, 0];
startrow = 1;   % Define the starting row in the data file

[mass] = xlsread('C:\Users\Ethan\Documents\MATLAB\Survival Analysis Optimization\Gx_test Numbers and
Weights.xlsx', 'Sheet1', 'B2:D83');
loadstruct = struct( ...
      'injured', false, ...
      'Mass', 0, ...
      'Fx', 0, ...
      'Fy', 0, ...
      'Fz', 0, ...
      'Mx', 0, ...
      'My', 0, ...
      'Mz', 0 ...
      );
loading = repmat(loadstruct, size(filenames,1), 1);
for i = 1:length(filenames)
   curfile = [filenames(i).folder '\' filenames(i).name];
%    if(strcmp(filenames(i).name(1,1:4),'PMHS'))
%        loading(i).injured = true;
%    end


   if(strcmp(filenames(i).name(1:4),'PMHS'))
```

```
    [num,~,~] = xlsread(curfile, 'Peak values');
    fnumber = str2double(filenames(i).name(6:9));

    [j,~]=find(mass(:,1)==fnumber);
    loading(i).Mass=mass(j,2);
    loading(i).injured = mass(j,3);

    col = find(loc>0);
    ds = size(num(startrow:end, col(1)));
    datasize = ds(1,1);
    if(loc(1)>0)
      loading(i).Fx = num(startrow:end,loc(1));
    else
      loading(i).Fx = zeros(datasize,1);
    end
    if(loc(2)>0)
      loading(i).Fy = num(startrow:end,loc(2));
    else
      loading(i).Fy = zeros(datasize,1);
    end
    if(loc(3)>0)
      loading(i).Fz = num(startrow:end,loc(3));
    else
      loading(i).Fz = zeros(datasize,1);
    end
    if(loc(4)>0)
      loading(i).Mx = num(startrow:end,loc(4));
    else
      loading(i).Mx = zeros(datasize,1);
    end
    if(loc(5)>0)
      loading(i).My = num(startrow:end,loc(5));
    else
      loading(i).My = zeros(datasize,1);
    end
    if(loc(6)>0)
      loading(i).Mz = num(startrow:end,loc(6));
    else
      loading(i).Mz = zeros(datasize,1);
    end
  else
    [num,~,~] = xlsread(curfile, 'NIJ Time History');
    fnumber = str2double(filenames(i).name(1,1:4));

    [j,~]=find(mass(:,1)==fnumber);
    loading(i).Mass=mass(j,2);
    loading(i).injured = mass(j,3);

    col = find(loc>0);
    ds = size(num(startrow:end, col(1)));
    datasize = ds(1,1);
    if(loc(1)>0)
      loading(i).Fx = 0.224809.*num(startrow:end,loc(1));
    else
      loading(i).Fx = zeros(datasize,1);
    end
    if(loc(2)>0)
      loading(i).Fy = 0.224809.*num(startrow:end,loc(2));
    else
      loading(i).Fy = zeros(datasize,1);
    end
    if(loc(3)>0)
      loading(i).Fz = 0.224809.*num(startrow:end,loc(3));
    else
```

```
        loading(i).Fz = zeros(datasize,1);
    end
    if(loc(4)>0)
        loading(i).Mx = 8.8507457676.*num(startrow:end,loc(4));
    else
        loading(i).Mx = zeros(datasize,1);
    end
    if(loc(5)>0)
        loading(i).My = 8.8507457676.*num(startrow:end,loc(5));
    else
        loading(i).My = zeros(datasize,1);
    end

    if(loc(6)>0)
        loading(i).Mz = 8.8507457676.*num(startrow:end,loc(6));
    else
        loading(i).Mz = zeros(datasize,1);
    end
  end

end
```

readYLoading

```
function [loading] = readYLoading(filenames)
% Written by: Michael Miller & Justin Williams
% Date: 05/22/2018
%
% INPUTS: 1, Path to Excel Files
%         2, List of Filenames
%
% This code reads the files provided to it and sorts the data into its
% individual components.
%
% OUTPUTS: 1, Raw Neck Loading
%% Define Location of Fx, Fy, Fz, Mx, My, Mz by column number
loc = [2, 3, 4, 5, 6, 7];
startrow = 1;   % Define the starting row in the data file
pmhsstartrow = 7;   % Define the starting row in the data file

[mass] = xlsread('C:\Users\Ethan\Documents\MATLAB\Survival Analysis Optimization\Gy_test Numbers and
Weights.xlsx', 'Sheet1', 'B2:D63');
loadstruct = struct( ...
    'injured', false, ...
    'Mass', 0, ...
    'Fx', 0, ...
    'Fy', 0, ...
    'Fz', 0, ...
    'Mx', 0, ...
    'My', 0, ...
    'Mz', 0 ...
    );
loading = repmat(loadstruct, size(filenames,1), 1);
for i = 1:length(filenames)
  curfile = [filenames(i).folder '\' filenames(i).name];
%    if(strcmp(filenames(i).name(1,1:4),'PMHS'))
%       loading(i).injured = true;
%    end
  [num,~,~] = xlsread(curfile, 'Time History');

  if(strcmp(filenames(i).name(1:4),'PMHS'))
    fnumber = str2double(filenames(i).name(1,5));
    sr = pmhsstartrow;
```

```
    else
      fnumber = str2double(filenames(i).name(1,1:4));
      sr = startrow;
    end
    [j,~]=find(mass(:,1)==fnumber);
    loading(i).Mass=mass(j,2);
    loading(i).injured = mass(j,3);


    loading(i).Fx = num(sr:end,loc(1));
    loading(i).Fy = num(sr:end,loc(2));
    loading(i).Fz = num(sr:end,loc(3));
    loading(i).Mx = num(sr:end,loc(4));
    loading(i).My = num(sr:end,loc(5));
    loading(i).Mz = num(sr:end,loc(6));
end
```

SetupOptimization5

```
% Perform Optimization
% Routine to calculate Survival Functions
clear all;
close all;
clc;
DataSets = [1; 1; 0];  % Data sets to be read, 1, indicates include this set in the analysis, [x; y; z];
Xloading = [];
Yloading = [];
Zloading = [];
if(DataSets(1)==1)
  path = 'C:\Users\Ethan\Documents\MATLAB\Survival Analysis Optimization\Gx Excel Data'; % Directory which contains
Gx excel files
  filenames = dir([path,'\*.xlsx']);
  %% STEP 2: Read Data
  Xloading = readXLoading(filenames);        % Raw neck loading time history with participant Mass
end
if(DataSets(2))
  path = 'C:\Users\Ethan\Documents\MATLAB\Survival Analysis Optimization\Gy Excel Data';          % Directory which
contains Gy excel files
  filenames = dir([path,'\*.xlsx']);

  %% STEP 2: Read Data
  Yloading = readYLoading(filenames);        % Raw neck loading time history with participant Mass
end
if(DataSets(3))
  path = 'C:\Users\Ethan\Documents\MATLAB\Survival Analysis Optimization\Gz Excel Data'; % Directory which contains
Gx excel files
  filenames = dir([path,'\*.xlsx']);
end
loading = [Xloading; Yloading; Zloading];

%% STEP 3: Determine Initial Parameters for Optimization
% Obtain fitting parameters for critical values
metric = false;
[fits, goodness] = fitfunctions(metric);
%% STEP 4: Begin Optimization
%Fit single parameters in front of critical values
xSelect = [1 1 1 1 1 1];    %Indicate independent parameters to fit. Values ordered Fx, Fy, Fz, Mx, My, Mz.
numparams = max(xSelect');
x = 1.0 .*ones(1,numparams);% Establish appropriate numbers of params
save('workdata');
[x,fval,exitflag,output] = fminsearch(@Opt3,x);
```

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14. ABSTRACT
The Air Force employs ejection seats in its high-performance aircraft. While these systems are intended to ensure aircrew safety, the ejection process subjects the aircrew to potentially injurious forces. System validation includes evaluation of forces against a standard which is linked to the probability of injury. The Muti-Axial Neck Injury Criteria (MANIC) was developed to account for forces in all six degrees of freedom. Unfortunately, the MANIC is applied to each of the three linear input directions separately and applies different criterion values for each direction. These three separate criteria create a lack of clarity regarding acceptable neck loading, leading to potential disputes during acquisition. Thus, the current research sought to adjust the MANIC formulation to provide clear, easy to interpret criterion values, a single MANIC formula independent of the direction(s) of input acceleration. We developed an optimization program that would run the survival analysis for each of the input axes. The feasibility of the joint optimization to produce a unified MANIC criterion are discussed as a potential method to increase the interpretability of the MANIC. Additionally, analysis was conducting to study the sensitivity of the MANIC threshold values to tests accomplished with higher accelerations and heavier helmet weights.

15. SUBJECT TERMS
Optimization, survival analysis, safety, neck injury, test and evaluation

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