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Summary of Available Craniomaxillofacial Injury Criteria for Use with the FOCUS Headform

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14. ABSTRACT
The Facial and Ocular CountermeasUre Safety (FOCUS) headform is an advanced tool for measuring and predicting facial and ocular injuries. Medically validated injury criteria have been developed for use with the FOCUS headform to predict the risk of facial and ocular injury due to blunt impact. The purpose of the current report is to review and summarize previously reported work that has been done to develop injury criteria for facial fractures to be used with the FOCUS headform. This report is intended to provide users with both a quick reference for using injury criteria developed for the FOCUS headform and references to the source materials.

15. SUBJECT TERMS
combat helmets, blunt impact protection, facial injury, eye injury, impact tests, injury criteria, biomechanical response, FOCUS headform

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Summary

Injuries to the face and eye can be debilitating or even fatal. In order to protect against face and eye injuries, materiel developers need medically validated tools such as anthropomorphic test devices that can be used to assess the risk of injury. To this end, the Facial and Ocular CountermeasUre Safety (FOCUS) headform was developed as an advanced tool designed to measure loads caused by blunt impacts to the face and eye. To date, seven medically validated injury criteria have currently been developed to predict the risk of facial fracture due to blunt impact. The purpose of the current report is to review the available injury criteria, provide a quick reference to the literature sources, and provide recommendations on the applications of the injury criteria with the FOCUS headform. Thus, the FOCUS headform can be used with the injury criteria to predict injury and assist in the development of effective countermeasures and personal protective equipment.

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Table of Contents

Table of Contents

List of Figures

List of Tables

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Introduction

Craniomaxillofacial (CMF) injuries can be debilitating or even fatal. Approximately 25% of all injuries seen during recent U.S. military conflicts have been CMF in nature (Owens et al., 2008; Lew, Walker, Wenke, Blackborne & Hale, 2010; Keller, Han, Galarneau, & Gaball, 2015). These injuries vary in severity and can often require extensive surgical intervention (Brennan, 2013). In the short term, CMF injuries directly affect a Service Member's ability to shoot, move, and communicate. In the long term, extensive facial traumas have been shown to decrease life satisfaction, alter perception of body image, as well as increase the rates of post-traumatic stress disorder, alcoholism, unemployment, and incarceration (Levine, Degutis, Pruzinsky, Shin & Persing, 2005).

Medically validated assessment tools are needed to develop countermeasures that effectively protect against CMF injuries. The Facial and Ocular CountermeasUre Safety (FOCUS) headform is a specialized anthropomorphic test device (ATD) designed specifically for assessing CMF injuries. Since the development of the headform, research has been conducted to develop medically validated injury criteria for predicting injury risk resulting from blunt impacts. The purpose of the current report is to review the injury criteria developed and provide a quick reference for their application.

The report is arranged in sections describing injury criteria based on anatomical region and impact direction. The sections briefly describe the results of the respective test series, the development of the injury criteria, and the biofidelity of the specific anatomical regions of the FOCUS headform. A general methods section is also provided to briefly describe the experimental methods common to all test series.

Background

The concept for the FOCUS headform was derived from the evaluation of helicopter air bag systems in the early 2000s. Helicopter air bags were designed to increase the protection from flail injuries (Shanahan and Shanahan, 1989). Early evaluations of the cockpit airbags indicated a potential for interaction between the airbags and occupants wearing night vision goggles. This increased concerns over the possibility of facial and ocular injuries to aviators involved in mishaps. In response, the U.S. Army Aeromedical Research Laboratory (USAARL) conducted a series of experiments to quantify the risk of these injuries. During testing however, the lack of (1) an ATD headform capable of measuring blunt impacts loads to the face and eye and (2) facial and ocular injury thresholds made relating the ATD response to a reliable injury metric challenging.

In response to these limitations in ATD technology, USAARL identified the need for an advanced ATD that developers of facial and ocular protection devices could use to evaluate new protection and mitigation concepts. The ATD would be anthropometrically accurate and capable of measuring face and eye impact loads. The Military Operational Medicine Research Program (MOMRP) of the U.S. Army Medical Research and Materiel Command (now known as the U.S. Army Medical Research and Development Command [USAMRDC]) funded USAARL, who in collaboration with Virginia Tech-Wake Forest Center for Injury Biomechanics and Denton ATD, Inc., developed the FOCUS headform.

The FOCUS headform was conceptualized to have segmented facial regions with corresponding load cells to measure facial response to blunt impact. The headform's face was divided into 10 sections based on anatomical regions (Figure 1A). The frontal bone, maxilla, zygoma, and orbits were split into left and right sections (about the midsagittal plane), whereas the nasal bone and mandible were represented as whole sections. The orbit, which consisted of a synthetic socket and biofidelic eye (Kennedy et al., 2007; Kennedy and Duma, 2010), was mounted to a single axis load cell to measure anterior-posterior (A-P) loads of up to 225 pounds (lb). All other sections were instrumented with three-axis load cells with a 1000-lb capacity. The headform is instrumented with angular rate sensors and linear accelerometers at the center of mass (Figure 1B). Additionally, the FOCUS headform is designed to interface with a Hybrid III neck (Figure 1C). The whole assembly is covered with a synthetic skin representing the anthropometry of a 50th percentile military male aviator (Haley, 1988).

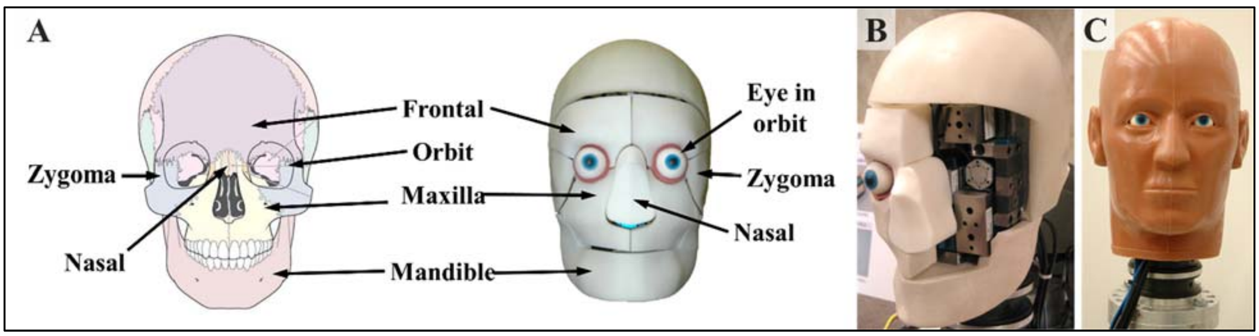

Figure 1. The FOCUS headform: (A) diagram of skull facial bones corresponding to FOCUS segmented facial regions, (B) an unassembled FOCUS headform showing the separate load cells, and (C) a fully assembled FOCUS headform mounted to a Hybrid III neck assembly.

Once the FOCUS headform development was completed, facial injury risk models were developed based off of the known failure limits of postmortem human subject (PMHS) facial bones. The biofidelic response of the headform was also evaluated. The FOCUS headform, along with its facial injury risk models, provides users with a tool to assess facial injuries.

Review of the Literature

A literature search returned several publications detailing facial bone injury risk functions and biofidelity assessments of the FOCUS headform. The literature included a combination of peer-reviewed journal papers, contractor and technical reports, dissertations, and conference presentations. For the purpose of the current report, the human eye injury risk functions and biofidelity of the FOCUS synthetic eye described by Kennedy et al. (2007) and Kennedy and Duma (2010) were not included due to the drastic difference in experimental testing methods.

Six sources were identified that described the development of human biomechanical response corridors and injury risk functions for A-P impacts to individual facial regions (Table 1); these sources also described the biofidelity of the FOCUS headform under A-P impacts

(Table 1). These sources include a doctoral dissertation, contractor reports, and peer-reviewed journal papers.

One literature source was identified that described the development of human biomechanical response corridors and injury risk functions for lateral impacts to individual facial regions (Table 1); this source also described the biofidelity of the FOCUS headform under lateral impacts (Table 1).

Table 1. Literature Sources used in the Technical Report

Bone	Impact Direction	Literature Sources
Frontal Bone	Anterior-Posterior	Cormier et al., 2008a Cormier, 2009; Cormier et al., 2010a Cormier et al., 2011a
	Lateral	Brozoski, 2012
Nasal Bone	Anterior-Posterior	Cormier et al., 2008a; Cormier, 2009; Cormier et al., 2010a Cormier et al., 2010b
	Lateral	Brozoski, 2012
Maxilla	Anterior-Posterior	Cormier et al., 2008a Cormier, 2009; Cormier et al., 2010a Cormier et al., 2011b
Mandible	Anterior-Posterior	Cormier et al., 2008a; Cormier, 2009
Zygoma	Lateral	Brozoski, 2012

Note. Table includes abbreviated citations. Full citations are located in the Reference section.

Experimental Methods

Two experimental methodologies will be described below: the first used PMHS to determine the risk of bone fracture, and the second used the FOCUS headform to determine the biofidelic response of the headform. All of the work was conducted by the Virginia Tech-Wake Forest Center for Injury Biomechanics; therefore, the research methods were fairly consistent for all facial bones.

Specimens

Impacts were performed in the A-P direction on four locations: frontal bone, nasal bone, maxilla, and mandible (Table 2). The PMHS specimens were prepared by removing the skin at the back of the head and affixing screws into the skull's occipital region. The screws provided additional contact surface area for rigidly mounting the specimen into a semi-circular support using a polyurethane resin. The specimens were positioned in a rigid support with the Frankfort plane vertical (Figure 2A). The FOCUS A-P impacts were performed at impact locations analogous to those of the PMHS specimens with the head oriented in a similar manner and mounted in a rigid support (Figure 2B).

Impacts were performed in the lateral direction on three locations: frontal bone, nasal bone, and zygoma (Table 2, Figure 2C). The PMHS specimens were rigidly mounted in a potting box fixture using a polyurethane resin. Screws drilled through the box fixture provided additional support. A total of 20 specimens were tested: 10 on the right side and 10 on the left. Frontal bone impacts were conducted first, since they do not influence the response of the other two bones. To quantify interaction effects, half (n = 10) of the specimens were first tested on the nasal bone and the other half were first tested on the zygoma. The FOCUS lateral impacts were performed at impact locations analogous to those of the PMHS specimens with the head oriented in a similar manner and mounted in a rigid support.

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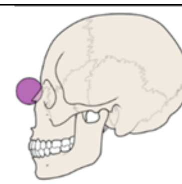
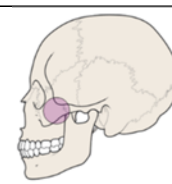
Table 2. Impactor Locations for Anterior-Posterior and Lateral Impacts of PMHS Specimens

	Bone	Impactor Locations	
Anterior-Posterior	Frontal Bone	Impactor lower edge was superior to the supraorbital ridge and centered to the orbit[1]	 2
	Nasal Bone	Impactor area was centered on the inferior surface of the nasal bone[1]	 2
	Maxilla	Impactor upper edge was inferior to the orbital rim and centered to the orbit[1]	 2
	Mandible	Impactor upper edge was inferior to the alveolar processes and centered to the midline of the chin[1]	 2
Lateral	Frontal Bone	Impactor area was centered between the forward-most aspect of the frontal bone and the coronal suture	 3
	Nasal Bone	Impactor area was centered on the anterior aspect of the nasal bones	 3
	Zygoma	Impactor area was centered on the zygoma	 3

Note. Table includes abbreviated citations. Full citations are located in the Reference section.
[1] Cormier et al. (2009).
[2] Adapted from figure published by Cormier et al. (2009).
[3] Brozoski (2012).

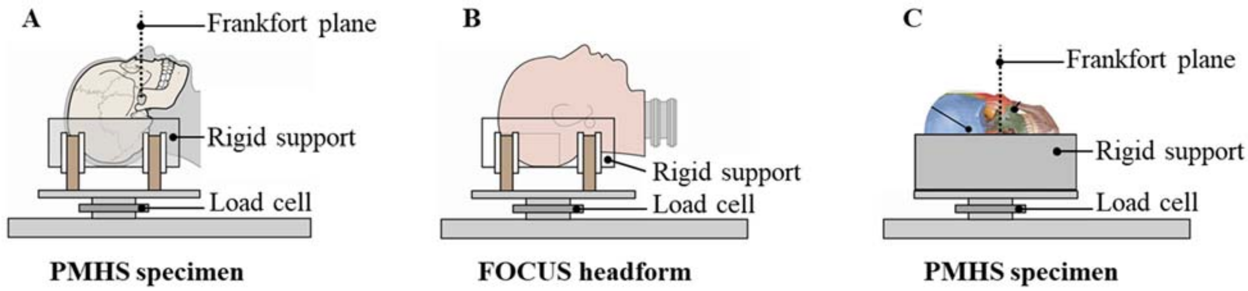


Figure 2. Specimen orientations for the PMHS and FOCUS test series. (A) Anterior-posterior impacts to PMHS, (B) A-P impacts to the FOCUS headform, and (C) lateral impacts to PMHS. Adapted from figures published by Cormier (2009) and Brozoski (2012).

Instrumentation

All A-P and lateral experimental tests (PMHS and FOCUS) were conducted using a gravity-driven drop tower with a 3.2-kilogram (kg), cylindrical, free-falling, rigid, aluminum impactor (Figure 3). The steel tip of the impactor was machined with a beveled edge to reduce edge effects and had a flat surface area of 6.45 cm^2. The impactor tip was instrumented with a load cell for measuring impact force. Additionally, the impactor was instrumented with two accelerometers: one atop the impactor mass and one collocated with the impactor load cell. Reaction forces were measured using a load cell mounted underneath the rigid support into which either the specimen or FOCUS were secured. All sensor data were sampled between 20,000 and 30,000 samples per second (Hz) and filtered to Channel Frequency Class 300. Impacts were documented using high-speed video recorded between 2000 and 4000 frames per second.

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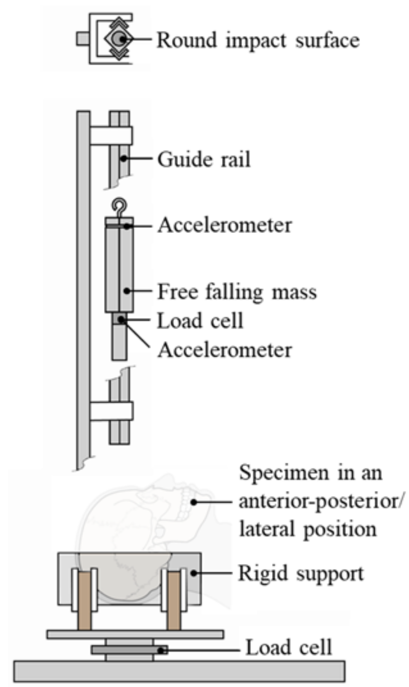

Figure 3. Schematic of the test apparatus and instrumentation used for all A-P and lateral experimental tests. Adapted from image published by Cormier et al. (2009). Anterior-posterior and lateral impacts were achieved by varying the orientation of the PMHS in the rigid support.

During PMHS tests, the time of bone fracture was determined using an acoustic emission (AE) sensor. The emissions detected during non-fracture and fracture tests were used to define an AE threshold associated with fracture (Cormier et al., 2008b). The time the AE signal exceeded the threshold was then used to obtain the time of fracture and corresponding fracture force. The AE sensor was adhered posterior to the apex of the frontal bone using cyanoacrylate adhesive and data were collected at rates between 2 and 5 megahertz (MHz) depending on the impact location. For the A-P impacts, an additional AE sensor was placed at the angle of the mandible to better capture the fracture times of the mandible and maxilla.

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Injury Risk Analysis

An injury criterion was developed for each facial bone using survival analysis methods that relate fracture force to the fracture risk. Data points were classified as either right censored (no fracture event occurred) or non-censored (NC; fracture event occurred at a known time). The times of fracture for non-censored data were determined through the analysis of AE signals (described above). Parametric and non-parametric methods were both used in the survival analyses to determine if the data censoring method affected the overall injury risk estimates.

The parametric method used the Weibull distribution to estimate the survival function. The Weibull distribution's cumulative distribution function (CDF) is given by Equation 1, where λ is the scale parameter, γ is the shape parameter, and F is the impactor force.

$$CDF = 1 - \exp[-(\lambda \cdot F)^{\gamma}] \qquad \text{Equation 1}$$

The non-parametric method used was the Kaplan-Meier estimator, which estimated the survival function in a step-wise manner (the equation used was not provided in the referenced literature). The literature sources (Table 1) show the results of both the parametric and non-parametric analysis methods. Forces corresponding to a 50% risk of injury, as predicted by the Weibull and Kaplan-Meier estimates, are presented within the current report. However, for the purposes of the current report, only the injury risk functions based on the parametric Weibull distribution are reproduced graphically. Readers are directed to the literature source documents for the full injury risk curves and further information on the non-parametric Kaplan-Meier survival analysis results.

Biomechanical Response Analysis

The PMHS data were further analyzed to evaluate the biomechanical response to loading. The PMHS and FOCUS responses were compared by assessing impactor force-displacement curves for a given impact location. Impactor displacement was determined through double integration of the impactor's acceleration and verified through video analysis. Initial contact (displacement = 0 mm) was defined as the first point that the impactor load cell exceeded 10 N. High-speed video was used to confirm this assumption. Force-displacement curves were created from initial contact to 90% of the peak force. The characteristic average and corridor were determined using the mean and standard deviation (SD), respectively, of the normalized force-displacement curves (Lessley, Crandall, Shaw, Kent, & Funk, 2004). The resulting corridors for PMHS and FOCUS tests were then overlaid to compare the biological and mechanical responses.

Experimental Results

Frontal Bone

Fracture tolerance.

Forty-six tests were conducted on 27 PMHS specimens to determine the frontal bone tolerance to fracture. The average specimen age was 73 years with a standard deviation of 14 years. Peak force ranged from 520 to 7600 N and impact energy ranged from 4 to 52 J. Twenty-two specimens sustained a fracture, which included depressed and stellate fracture patterns. An AE sensor threshold of 9 V was used to determine time of fracture. Force at fracture ranged from 890 to 3500 N (M = 1982, SD = 765) and was found to be unrelated to impactor energy or impactor velocity.

Three injury criteria were generated for the frontal bone. The first criterion used the parametric method and estimated a 50% risk of fracture at 2523 N (Figure 4).[1] The second criterion also used the parametric method (Figure 4); however, data points associated with injury were assumed to have a fracture event sometime between the first above-threshold AE signal and the time of peak force (interval censored [IC]). Again, all data points not associated with injury were assumed to be right censored. The second criterion was considered less conservative, giving a 50% risk of fracture at 3540 N.[1] The third criterion used the non-parametric Kaplan-Meier estimate and resulted in a 50% risk of fracture at 1950 N.[2]

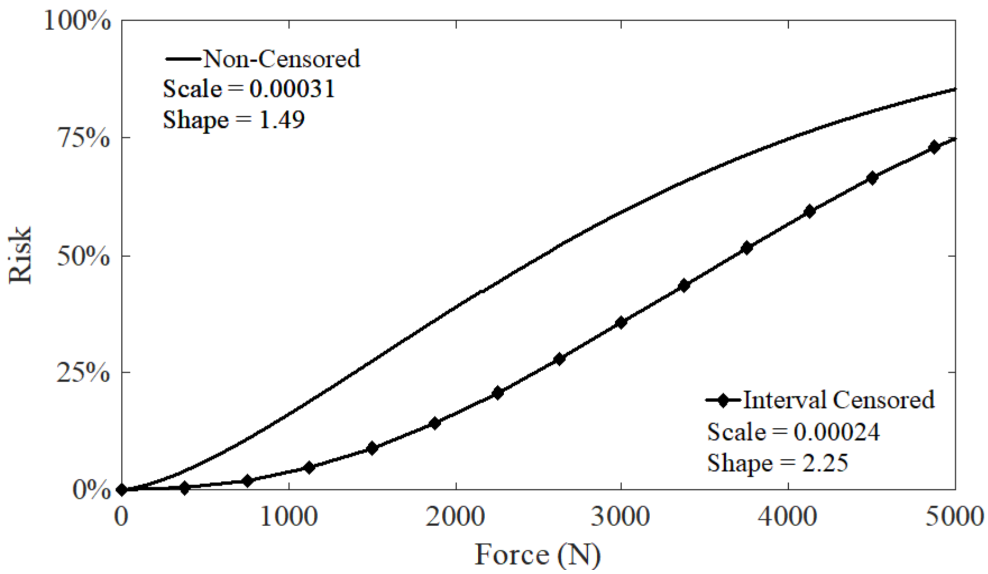

Figure 4. Risk of frontal bone fracture during A-P impact. The two models were estimated using a Weibull distribution with fracture events treated as either non-censored or interval censored.[3] [Figure reproduced using Weibull distribution parameters provided (Cormier et al., 2011a)].

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[1] The reported number was obtained using the Weibull model provided by Cormier et al. (2011a).
[2] The reported number was obtained through digitization of the figure published by Cormier et al. (2011a).
[3] Both models converge to predict the 100% fracture risk at force levels greater than 5000 N. The x-axis has been truncated at the maximum capacity of the frontal bone load cell of the FOCUS headform: 5000 N.

Biomechanical response.

Twenty frontal bone tests from 15 of the specimens were assessed. The average specimen age was 73 years with a standard deviation of 16 years. Impact velocity ranged from 1.6 to 5.7 m/s and peak force ranged from 945 to 5934 N. Five of the 15 specimens sustained fractures.

Six tests were conducted on the FOCUS headform to determine the mechanical response to loading. Impact velocity ranged from 2.0 to 2.2 m/s, and impact energy ranged from 6.3 to 7.9 J. Impact force ranged from 2754 to 3260 N. The impactor load cell and headform load cell data were consistent with a 0.3% average difference in peak force.

The PMHS and FOCUS force-displacement corridors were generated to compare the response of each model (Figure 5). When overlaid, the entire FOCUS corridor was found to mostly fit within the lower standard deviation of the PMHS corridor. Results indicate the FOCUS headform would produce reaction forces in line with the PMHS model and the resulting injury criteria created for the PMHS will be applicable to the FOCUS headform.

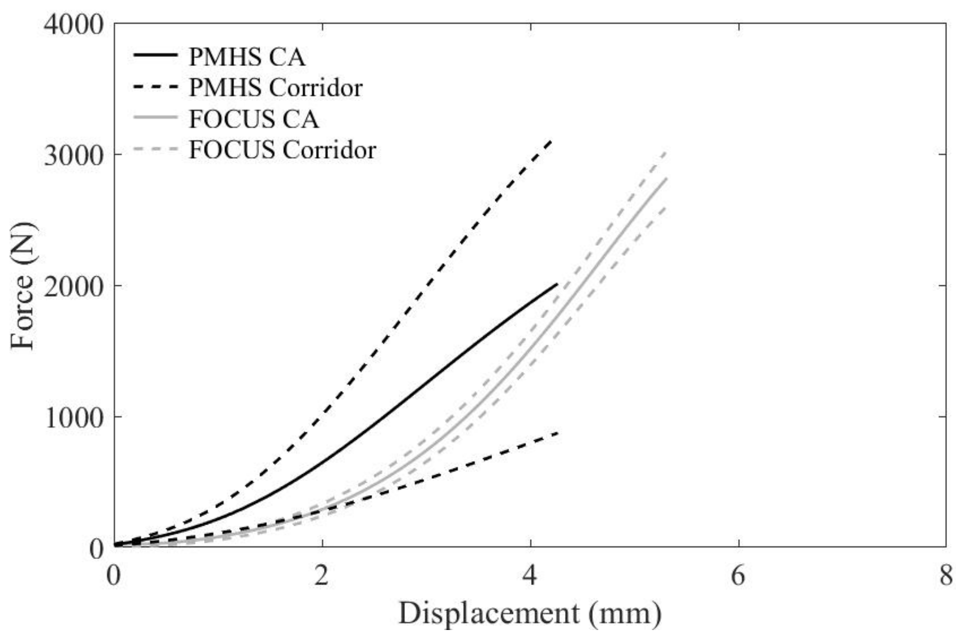

Figure 5. Force-displacement response for PMHS and FOCUS frontal bone impacts. The response was given by the characteristic average (CA) and corridor (CA ± one standard deviation of the force [SD]). [Figure adapted from data reproduced through digitization of published figure (Cormier, 2009)].

Nasal Bone

Fracture tolerance.

Twenty-four tests were conducted on 24 PMHS specimens to determine the fracture tolerance of the nasal bone. The average specimen age was 71 years with a standard deviation of 15 years. Peak force ranged from 784 to 2260 N and impact energy ranged from 4 to 16 J. Twenty-three specimens sustained a fracture during testing. Fracture patterns included depressed and comminuted fractures. Slight separation of the nasal bone and maxilla was also observed. An AE sensor threshold of 9 V was used to determine time of fracture. Force at fracture ranged from 106 to 1767 N (*M* = 664, *SD* = 434). Fracture force was determined not to be related to impactor energy, impactor velocity, or nasal bone anthropometry. However, fracture force was found to have a negative correlation with age, with results showing that as age increased, the fracture force decreased.

Two injury criteria were generated for the nasal bone. The first criterion used the parametric method and estimated a 50% risk of fracture at 616 N (Figure 6).[4] Age was evaluated as a covariate and found to be statistically significant; however, further testing was deemed necessary to include age as a model parameter. The second criterion used the non-parametric Kaplan-Meier estimate and resulted in a 50% risk of fracture at 600 N.[5]

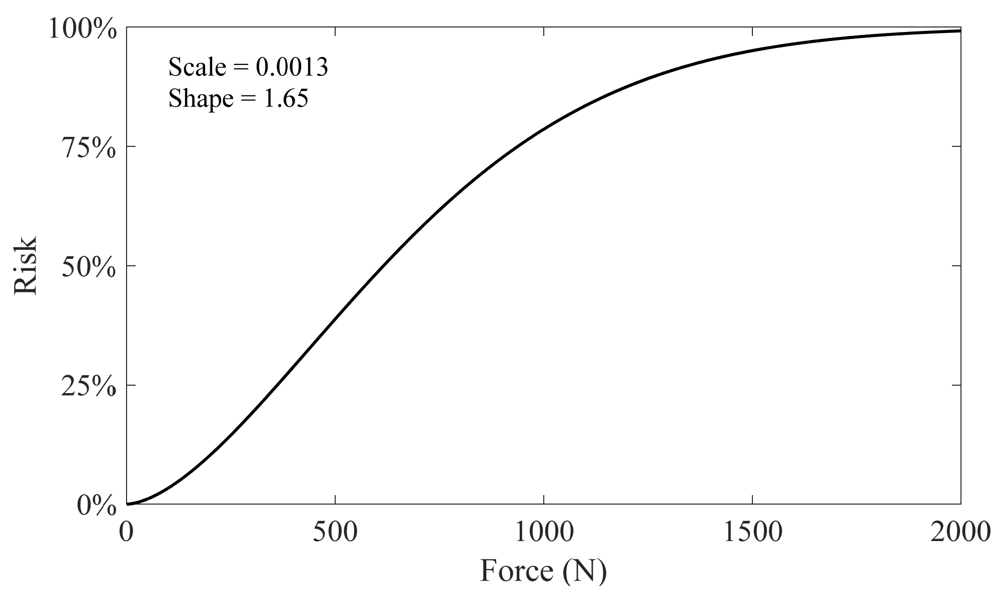

Figure 6. Risk of nasal fracture due to an A-P impact. [Figure reproduced using the Weibull distribution parameters provided (Cormier et al., 2010b)].

[4] The reported number was obtained using the Weibull model provided by Cormier et al. (2010b).
[5] The reported number was obtained through digitization of the figure published by Cormier et al. (2010b).

Biomechanical response.

Nineteen nasal bone tests from 19 of the specimens were assessed. The average specimen age was 68 years with a standard deviation of 13 years. Impact velocity ranged from 1.6 to 3.2 m/s and peak force ranged from 784 to 2185 N. Eighteen of the 19 specimens experienced fractures.

Four tests were conducted on the FOCUS headform to determine its response to loading. An impact velocity of 2.2 m/s, corresponding to an impact energy of 8 J, was used for all tests. The average impact force was 4110 N (*SD* = 37). The impactor load cell and headform load cell data were found to be consistent with a 2.0% average difference in peak force.

The PMHS and FOCUS force-displacement corridors were generated to compare the response of each model (Figure 7). When the responses were overlaid, the FOCUS was found to have a different response than the PMHS. The soft FOCUS nasal insert led to a much longer initial toe region followed by a very stiff secondary response. The PMHS response was very wide as the individual responses varied significantly. The variation was attributed to the different geometries of the nasal region that led to varying amounts of deflection required to deform the nose and varying amounts of force generated between the interactions of the impactor with the nasal bones. The FOCUS nasal response varied according to the impact location, therefore, improvements of the FOCUS's nasal bone biofidelity was recommended.

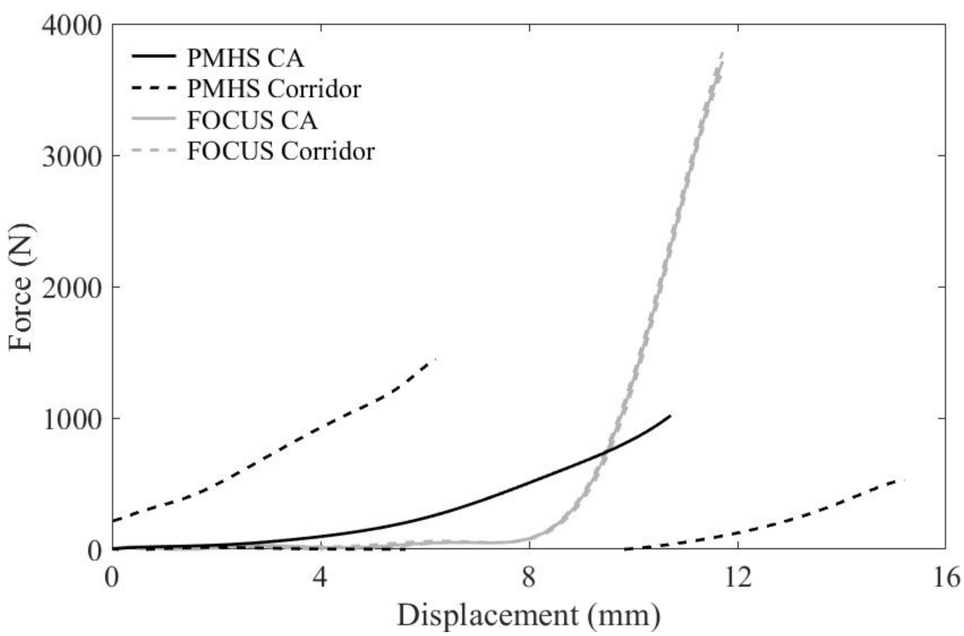

Figure 7. Force-displacement response for PMHS and FOCUS nasal bone impacts. The response was given by the characteristic average (CA) and corridor (CA ± extremes of the standard deviations for both force and displacement). The normalization process (Lessley, Crandall, Shaw, Kent, & Funk, 2004) used to determine the corridor caused a portion of it to fall below the x-axis as well as indicate non-zero forces at zero displacement. [Figure adapted from data reproduced through digitization of published figure (Cormier et al., 2009)].

Maxilla

Fracture tolerance.

Thirty-eight tests were conducted on PMHS 24 specimens to determine the maxilla tolerance to fracture. The average specimen age was 67 years with a standard deviation of 14 years. Peak force ranged from 644 to 2609 N and impact energy ranged from 3 to 44 J. Twenty specimens sustained a fracture. An AE sensor threshold of 9 V was used to determine time of fracture. Force at fracture ranged from 420 to 2570 N (M = 1138, SD = 551).

Two injury criteria were generated for the maxilla. The first criterion used the parametric method and estimated a 50% risk of fracture at 1226 N (Figure 8).[6] The second criterion used the non-parametric Kaplan-Meier estimate and resulted in a 50% risk of fracture at 1200 N.[7]

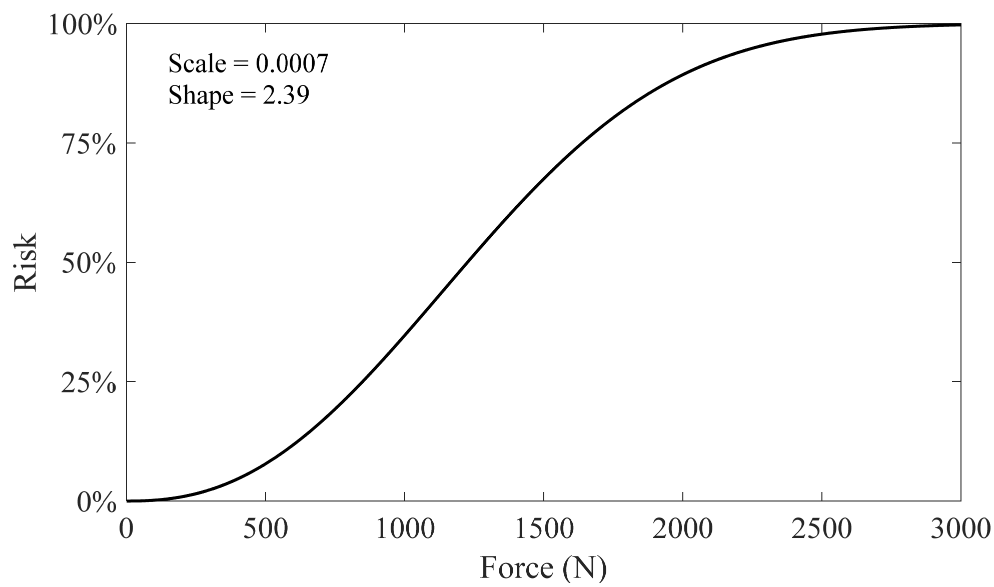

Figure 8. Risk of maxillary fracture due to an A-P impact. [Figure reproduced using the Weibull distribution parameters provided (Cormier et al., 2009)].

[6] The reported number was obtained using the Weibull model provided by Cormier et al. (2011b).
[7] The reported number was obtained through digitization of the published figure by Cormier et al. (2011b).

Biomechanical response.

The PMHS data were further analyzed to evaluate the biomechanical response to loading. Twenty-nine maxilla tests from 19 of the specimens were assessed. The average specimen age was 66 years with a standard deviation of 15 years. Impact velocity ranged from 1.4 to 5.2 m/s and peak force ranged from 644 to 2023 N.

Nine tests were conducted on the FOCUS headform to determine the mechanical response to loading. Impact velocity ranged from 2.4 to 2.8 m/s and impact energy ranged from 9.4 to 12.6 J. Impact force ranged from 1485 to 1769 N. Impactor and FOCUS load cell data had an average difference in peak force of 14%.

The PMHS and FOCUS force-displacement corridors were generated to compare the response of each model (Figure 9). When overlaid, FOCUS was found to have a similar response to the PMHS. The FOCUS force-displacement curves match the PMHS characteristic average indicating that it would produce forces similar to those produced in the PMHS model.

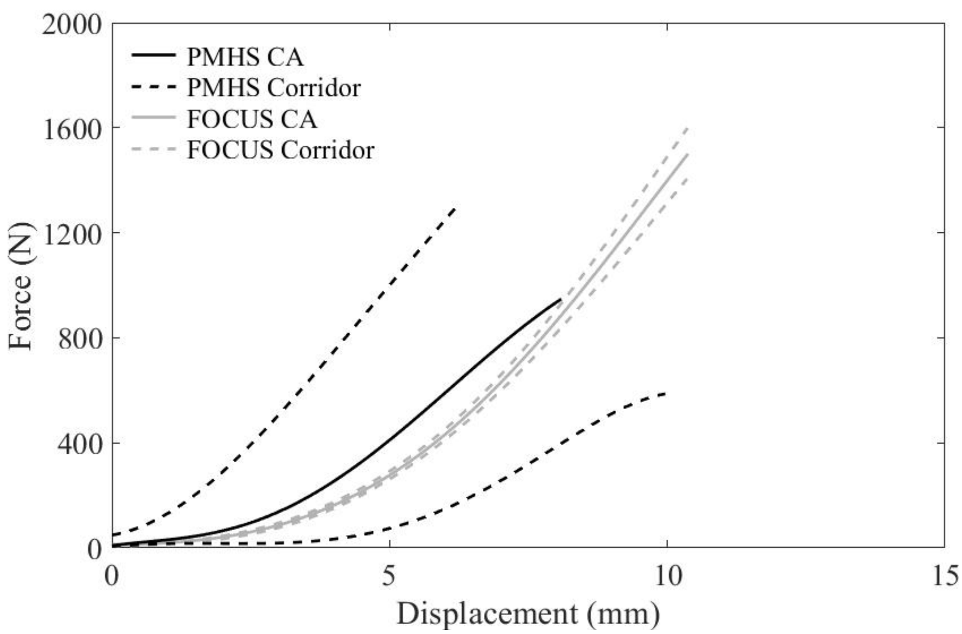

Figure 9. Force-displacement response for PMHS and FOCUS maxilla impacts. The response was given by the characteristic average (CA) and corridor (CA ± extremes of the standard deviations for both force and displacement). The normalization process (Lessley, Crandall, Shaw, Kent, & Funk, 2004) used to determine the corridor caused it indicate non-zero forces at zero displacement. [Figure adapted from data reproduced through digitization of published figure (Cormier et al., 2009)].

Mandible

Fracture tolerance.

Thirty-one tests were conducted on 29 PMHS specimens to determine the mandible tolerance to fracture. The average specimen age was 69 years with a standard deviation of 14 years. Peak force ranged from 402 to 1607 N and impactor energy ranged from 8 to 59 J. Four specimens sustained a fracture and six specimens sustained fracture of the alveolar processes; however, the alveolar process fractures were not included in the analysis. An AE sensor threshold varying from 5 to 9 V was used to determine time of fracture. Force at fracture ranged from 601 to 1098 N (*M* = 805, *SD* = 210).

Two injury criteria were generated for the mandible. The first criterion used the parametric method (Figure 10) and estimated a 10% risk of fracture at 890 N.[8] The second criterion used the non-parametric Kaplan-Meier estimate and resulted in a 10% risk of fracture at 770 N.[9] Due to the limited number of fracture data points, neither model reached a 100% risk of injury.

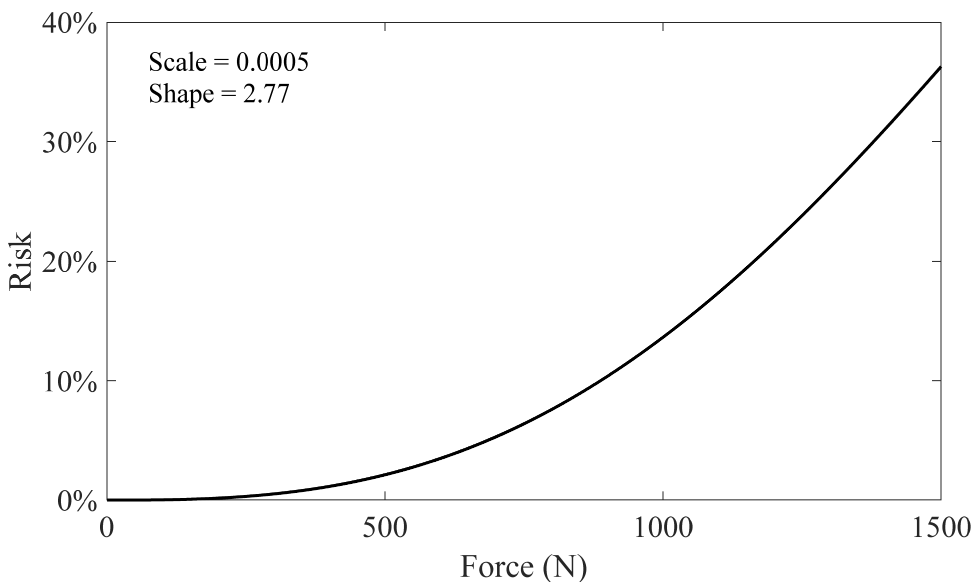

Figure 10. Risk of mandible fracture due to an A-P impact. [Figure reproduced using the Weibull distribution parameters provided (Cormier, 2009)].

[8] The reported number was obtained using the Weibull model provided by Cormier. (2009).
[9] The reported number was obtained through digitization of a figure from Cormier. (2009).

Biomechanical response.

At least 20 tests were used to assess the PMHS mandible response to blunt impact; however, specimen information (specimen ID, age, etc.) and impact results (velocity, energy, force, etc.) were not reported. Five tests were conducted on the FOCUS headform to determine the mechanical response to loading. Impact velocity ranged from 2.8 to 3.2 m/s and impact energy ranged from 12.7 to 15.7 J. Impact force ranged from 1874 to 2032 N. Impactor and headform load cell data had an average difference in peak force of 0.8%.

The PMHS and FOCUS force-displacement corridors were generated to compare the response of each model (Figure 11). When overlaid, the FOCUS corridors were found to fit between the mean and upper standard deviation of the PMHS model. Overall, the FOCUS force-displacement response was similar to that of the PMHS model.

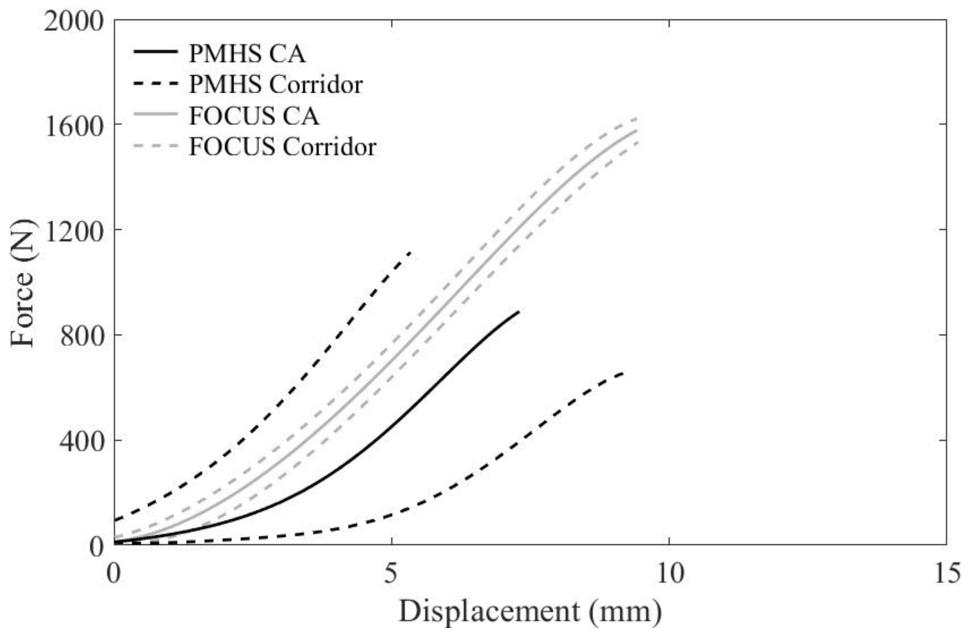

Figure 11. Force-displacement response for PMHS and FOCUS mandible impacts. The response was given by the characteristic average (CA) and corridor (CA ± extremes of the standard deviations for both force and displacement). The normalization process (Lessley, Crandall, Shaw, Kent, & Funk, 2004) used to determine the corridor caused it to indicate non-zero forces at zero displacement. [Figure adapted from data reproduced through digitization of published figure (Cormier, 2009)].

Lateral Frontal Bone

Fracture tolerance.

Twenty-four tests were conducted on 20 PMHS specimens to determine the lateral frontal bone tolerance to fracture (Brozoski, 2012). Specimen age was not reported. Velocity ranged from 0.8 to 6.4 m/s and impactor energy ranged from 1.1 to 64.3 J. Peak force ranged from 352 to 8886 N. Eighteen specimens sustained fracture during testing; fractures included non-depressed radiating fractures and depressed comminuted fractures. An AE sensor threshold of 5 V was used to determine time of fracture. Force at fracture ranged from 664 to 3870 N (M = 1994, SD = 909).

Two injury criteria were presented in Brozoski (2012); however, due to inconsistencies between the equation, the generated injury risk curve figure, and the text, these criteria are not presented in the current study. However, the data presented within Brozoski (2012) was used to create an injury criteria based on a Weibull distribution and Equation 1. For this injury criteria, fractured data points were treated as uncensored and the fracture force identified by AE sensors was used in the analysis. Specimens that did not fracture from the testing were treated as non-fractured data points, where the peak force was used and treated as right-censored. The developed injury criteria estimated that the 50% risk of fracture would occur at 2382 N (Figure 12). While Brozoski (2012) found age to be statistically significant, age was not a variable in the calculated injury criteria presented within this study due to specific specimen ages not being reported.

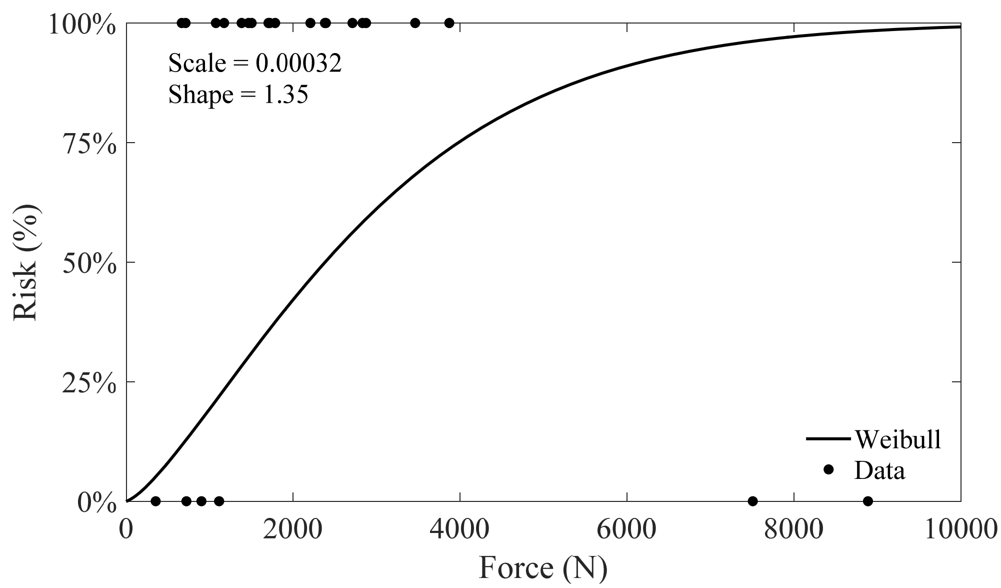

Figure 12. Risk of frontal bone fracture due to a lateral impact. The injury criteria was developed using a Weibull distribution with the data presented within Brozoski (2012).

Biomechanical response.

Sixteen tests from an unknown number of specimens were assessed (Brozoski, 2012). Specimen information was not provided; therefore, the number of fractures and impact conditions were not available. Ten tests were conducted on the FOCUS headform to determine the mechanical response to loading. Impacts were conducted at velocities of 2.0 and 2.23 m/s, corresponding to target impact energy of 6.29 and 7.86 J, respectively. Impact force ranged from 1860 to 2253 N. The PMHS and FOCUS force-displacement corridors were generated to compare the response of each model (Figure 13). When overlaid, the FOCUS response was found to have a similar response to the PMHS model, fitting just above the characteristic average.

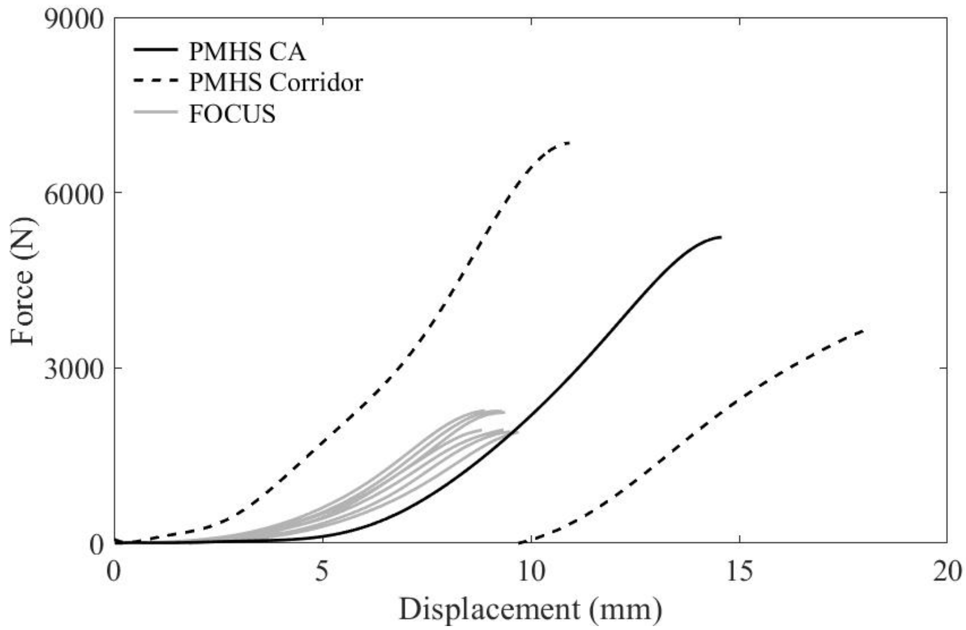

Figure 13. Lateral frontal bone response during PMHS and FOCUS testing. The response was given by the characteristic average (CA) and corridor (CA ± extremes of the standard deviations for both force and displacement). Note that the PMHS plot reflects the CA and corridor while the FOCUS plot reflects the individual tests. The normalization process (Lessley, Crandall, Shaw, Kent, & Funk, 2004) used to determine the corridor caused a portion of it to fall below the x-axis. [Figure adapted from data reproduced through digitization of published figure (Brozoski, 2012)].

Lateral Nasal Bone

Fracture tolerance.

Nineteen tests were conducted on 19 PMHS specimens to determine the lateral nasal bone tolerance to fracture. Specimen age was not reported. Brozoski (2012) reported that the velocity ranged from 2.1 to 2.5 m/s and the impactor energy ranged from 6.7 to 9.6 J. Peak force ranged from 76 to 723 N. Eighteen specimens sustained fracture during testing. Fracture patterns included fracture to the nasal bone itself, as well as fracture of the medial aspect of the maxilla. Maxillary fractures occurred both on the side of impact as well as the contralateral side. Additionally, impacts were noted to have caused the nose to translate through bending of the soft tissue. An AE sensor threshold of 5 V was used to determine time of fracture. Force at fracture ranged from 61 to 410 N (M = 122, SD = 82).

Two injury criteria were generated for the lateral nasal bone. The first criterion used a parametric Weibull distribution and in order to determine the risk of fracture, the published figure was reproduced. The reproduced figure was created by digitizing the original published figure and determining the appropriate parameters of Equation 1 to best match the digitized graph. Through this process, the 50% risk of fracture was estimated to occur at 115 N (Figure 14). The second criterion used the non-parametric Kaplan-Meier estimate and yielded a 50% risk of fracture at 103 N.[10]

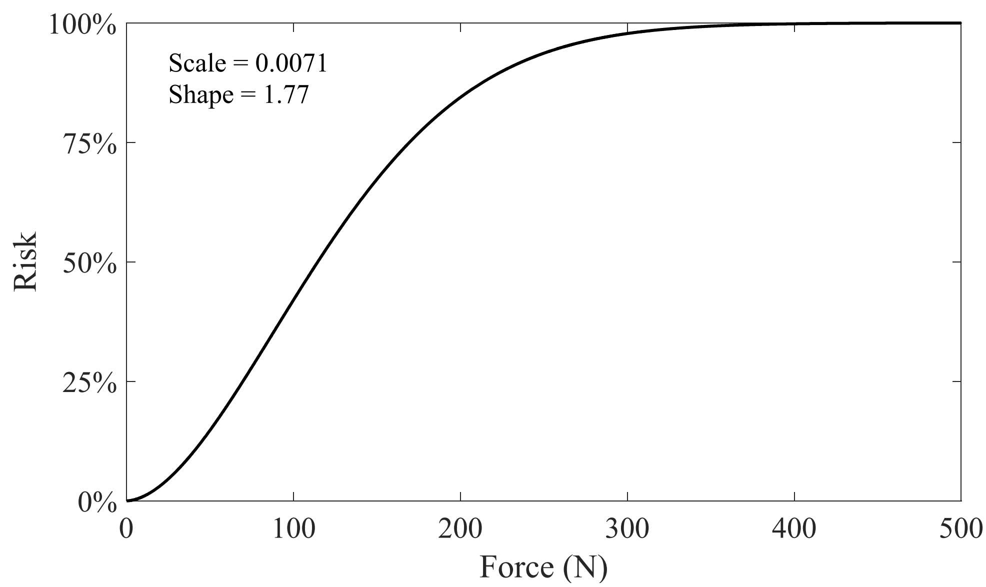

Figure 14. Risk of nasal bone fracture due to a lateral impact. [Figure reproduced through digitization of published figure (Brozoski, 2012) with the appropriate Equation 1 parameters determined to best match the digitized graph].

[10] The reported number was obtained by digitization of the figure published by Brozoski (2012).

Biomechanical response.

Twelve PMHS tests were selected to assess the lateral nasal bone response to blunt impact. Specimen information was not provided; therefore, the number of fractures and impact conditions were not available. Two tests were conducted on the FOCUS headform to determine the mechanical response to loading. Impacts were conducted at velocities of 2.0 and 2.23 m/s, corresponding to target impact energy of 6.29 and 7.86 J, respectively. Impact force ranged from 765 to 844 N.

The PMHS and FOCUS force-displacement corridors were generated to compare the response of each model (Figure 15). When overlaid to assess the similarities in response, FOCUS was found to have a stiffer nasal bone response with good comparison under 2.5 mm deflection. Generally, the FOCUS response gave a conservatively high measurement of nasal bones response.

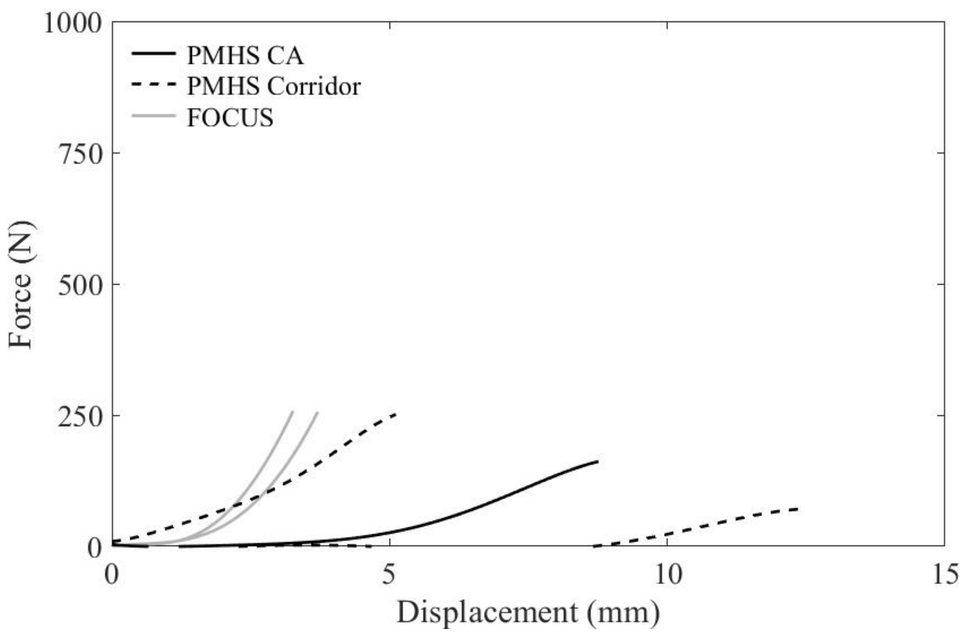

Figure 15. Lateral nasal bone response during PMHS and FOCUS testing. The response was given by the characteristic average (CA) and corridor (CA ± extremes of the standard deviations for both force and displacement). Note that the PMHS plot reflects the CA and corridor while the FOCUS plot reflects the two individual tests. The normalization process (Lessley, Crandall, Shaw, Kent, & Funk, 2004) used to determine the corridor caused portions of it to fall below the x-axis. [Figure adapted from data reproduced through digitization of published figure (Brozoski, 2012)].

Lateral Zygoma

Fracture tolerance.

Seventeen tests were conducted on 17 PMHS specimens to determine the lateral nasal bone tolerance to fracture. Specimen age was not reported. Velocity ranged from 3.8 to 4.6 m/s and impactor energy ranged from 22.4 to 32.7 J. Peak force ranged from 913 to 2835 N. All specimens sustained a fracture during testing. Fracture patterns included medial and lateral fractures of the zygoma. Medial fractures propagated along the suture line between the zygoma and frontal process of the maxilla. Lateral fractures occurred at the zygomatic arch and frontal process. An AE sensor threshold of 5 V was used to determine time of fracture. Force at fracture ranged from 504 to 2792 N (M = 906, SD = 570).

Two injury criteria were generated for the zygoma. The first criterion used a parametric Weibull distribution and in order to determine the risk of fracture, the published figure was reproduced. The reproduced figure was created by digitizing the original published figure and determining the appropriate parameters of Equation 1 to best match the digitized graph. Through this process, the 50% risk of fracture was estimated to occur at 834 N (Figure 16). The second criterion used the non-parametric Kaplan-Meier estimate and yielded a 50% risk of fracture at 672 N.[11]

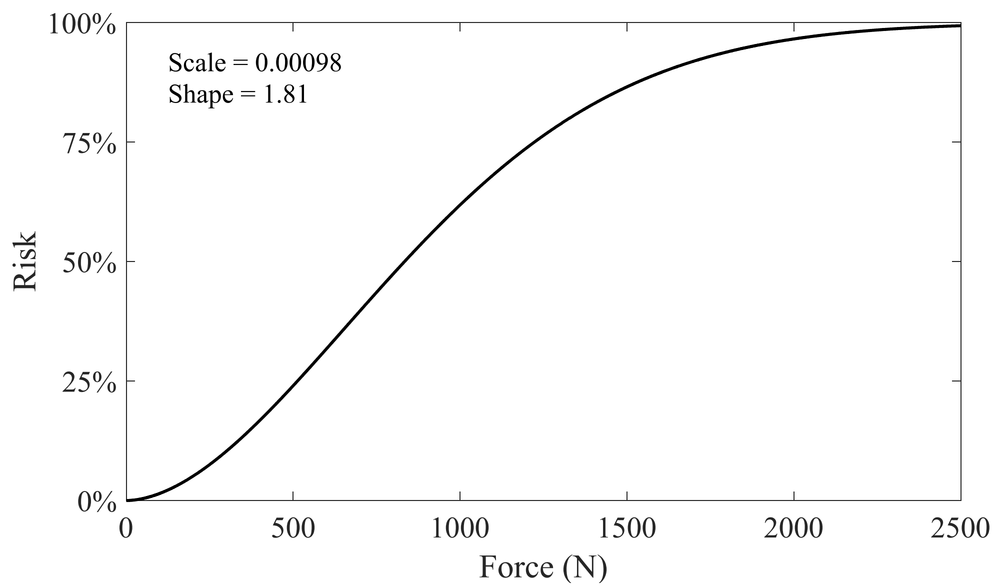

Figure 16. Risk of zygoma fracture due to a lateral impact. [Figure reproduced through digitization of published figure (Brozoski, 2012) with the appropriate Equation 1 parameters determined to best match the digitized graph].

[11] The reported number was obtained by digitization of the figure published by Brozoski (2012).

Biomechanical response.

Sixteen PMHS tests were selected to assess the lateral zygoma bone response to blunt impact. Specimen information was not provided; therefore, the number of fractures and impact conditions were not available. Ten tests were conducted on the FOCUS headform to determine the mechanical response to loading. Impacts were conducted at velocities of 2.0 and 2.23 m/s, corresponding to target impact energy of 6.29 and 7.86 J, respectively. Impact force ranged from 1349 to 1637 N.

The PMHS and FOCUS force-displacement corridors were generated to compare the response of each model (Figure 17). When overlaid to assess the similarities in response, the FOCUS response was observed to fit well within the corridor created from PMHS testing. While FOCUS was found to have a slightly stiffer response than that of the average PMHS response, it was still within the upper bound of the PMHS corridors.

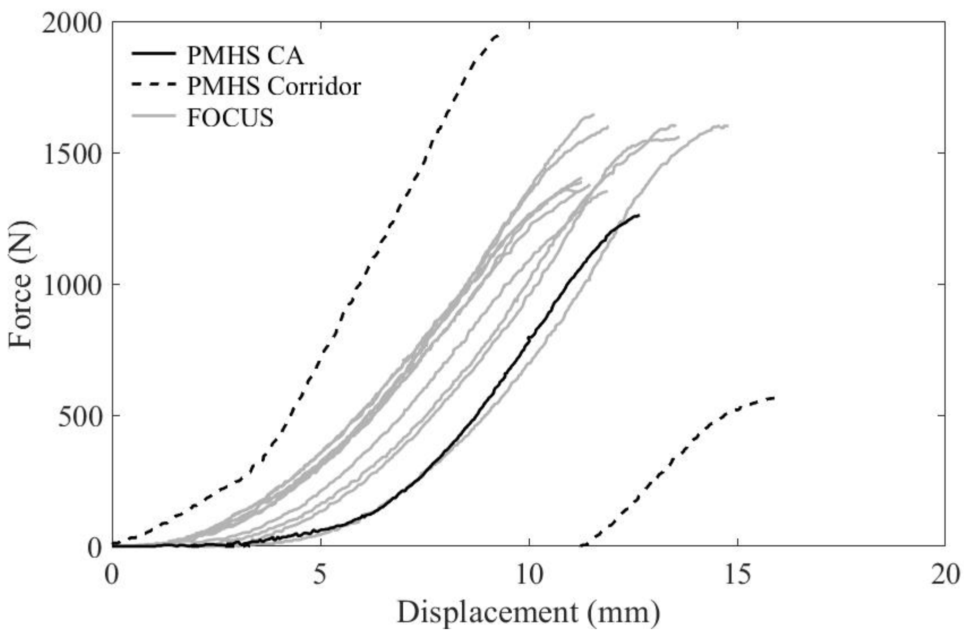

Figure 17. Lateral zygoma bone response during PMHS and FOCUS testing. The response was given by the characteristic average (CA) and corridor (CA ± extremes of the standard deviations for both force and displacement). Note that the PMHS plot reflects the CA and corridor while the FOCUS plot reflects the individual tests. The normalization process (Lessley, Crandall, Shaw, Kent, & Funk, 2004) used to determine the corridor caused a portion of it to fall below the x-axis. [Figure adapted from data reproduced through digitization of published figure (Brozoski, 2012)].

Discussion

There are several general limitations in the development of injury criteria for the FOCUS headform. These limitations were either identified in the original literature sources or from this review, and they should be considered in future test preparations and/or analyses.

Experimental

The impactor used during testing had a single impact surface geometry and the effect of the impact surface area (including shape) was not investigated. The shape of the impactor was partly dictated by the need to ensure that a single bone was impacted so that injury tolerances for specific bones could be determined. Variation in the impactor shape may affect the injury response. Impactor contact area was assessed using pressure mapping and showed that the entire impactor was not in contact with the bone(s) during impact (Cormier et al., 2009). Therefore, similar responses with smaller impact surfaces might be expected. Additionally, this might also be true of larger impact surfaces where the impactor would interact more with the bone and thus the geometry of the bone would become the limiting factor. This was demonstrated by the sensitivity of the response for nasal region to the geometry of the nasal bones (Cormier et al., 2010a).

In addition to the impactor shape, the large ranges in chosen impact velocity for some of the locations in the PMHS tests were also identified as a limitation. The wide range of impact velocities in the PMHS tests for these locations (Frontal bone [A-P and lateral], Nasal bone [A-P], and Maxilla [A-P]), caused a wider distribution of peak force values. The correlating FOCUS tests were then completed with a smaller range of impact velocities. Thus, the corridors in the force-displacement plots appear to be wider for the PMHS tests. However, the difference in the range of impact velocities between the FOCUS and PMHS tests may account for some of that variation.

Biological

Several biological considerations exist as well. Only male specimens were evaluated and gender effects could not be addressed. Further work should examine fracture tolerances in a female population. The effect of age was evaluated as most of the specimens were older than the population of interest; however, no test series was able to assess specimens under the age of 40 years. It remains unknown how these tests would compare to those performed on younger specimens, but it could be inferred that injury criteria for older populations represent a more conservative estimate of injury risk.

Mandible

Of all bone regions tested, the mandible was the facial region that had the most experimental issues. The major limitation for the mandible was the low number of fractures created during testing that resulted in the injury risk function's inability to reach 100% risk. The low number of fractures was attributed to the jaw displacing during impact and dissipating the energy. Besides a low number of fractures, the lack of teeth in the specimens might have affected the force of fracture. Cormier (2009) notes that the majority of the specimens were edentulous, which is most likely due to their advanced age. Cormier et al. (2008a) attempted to use data collected during previous studies to suggest an injury criteria; however, this might not be reasonable due to changes in the experimental setups. Regardless, future work is needed to develop a more robust anterior-posterior injury criterion and a lateral mandible injury criterion.

Survival Analysis

Within the published works, the results of the injury risk analysis were not always reported consistently across facial bone regions. Some papers presented the 50% risk of injury as a point value while others presented it as a range. This was true for both the parametric and non-parametric methods. In some cases, a recommended value (different than that reported for either model) was presented. Additionally, in some cases the published survival analysis model parameters were not able to reproduce the model shown in the published figures. For those that were not reproduced from the survival analysis model parameters, it was assumed that the published figures were correct and the figures were reproduced using digitization techniques. The digitized figures for the Weibull distributions were then used to calculate the appropriate parameters to best fit the digitized injury risk curves. This applies to the nasal bone and zygoma lateral injury risk curves derived from Brozoski (2012). In the case of the frontal bone lateral injury risk curve, inconsistencies in the referenced literature prevented the published injury criteria from being reproduced. Therefore, it was assumed that the published peak and fracture forces were correctly identified, and those values were used to develop a new injury criteria.

Recommendations for Use

Based upon the review of the source material, six injury criteria were developed for assessment of facial fracture tolerance. The mandible injury criterion was not able to fully converge to a 100% risk of fracture and, thus, is not recommended for use. Table 3 provides the 50% risk of injury based on facial location and impact direction as well as the corresponding FOCUS data channel that should be used to measure the force.

When assessing the risk of injury using the FOCUS headform, it is recommended to use the parametric analysis using a Weibull distribution to determine the risk of injury. The parameters for each facial bone risk of injury model are provided in Appendix A. Tables B1 and B2 in Appendix B give the approximate risk of injury in 10% intervals for use as a quick reference tool in estimating the risk of injury for anterior-posterior and lateral impacts, respectively. Additionally, the 95% confidence intervals for the Weibull model parameters were used to estimate the range of fracture force at discrete risk levels and results are available for anterior-posterior impacts in Appendix C. For best results, data should be filtered using the same technique as the one used to develop the referenced injury criteria (i.e., CFC 300). In addition, the sample rate should be set at a high enough rate to allow for this filter to be used in the data analysis.

The biofidelity of the FOCUS headform was also reviewed for the seven facial bone locations. The FOCUS headform was found to have a biofidelic response for all impacted locations except the nasal bone. For all of the facial locations that were considered to be biofidelic, it could be assumed that the FOCUS response will match the PMHS response. The only locations not considered to be biofidelic were the FOCUS nasal and mandible regions. However, ongoing research at USAARL is being performed to develop both an injury risk criteria and the biofidelic response associated with the FOCUS headform for the mandible. In regards to the other locations, data collected using the FOCUS headform can be analyzed using the developed injury criteria to determine the risk of injury.

Table 3. FOCUS Forces Correlated to 50% Risk of Injury for each Facial Location

Bone	Direction	Force at 50% Risk of Injury* (N)
Frontal Bone	A-P	2523
	Lateral	2382
Nasal Bone	A-P	616
	Lateral	115
Maxilla	A-P	1226
Zygoma	Lateral	834
Mandible	A-P	NA

* Based on parametric analysis using the Weibull distribution

Conclusion

A review of the currently available literature shows that injury criteria have been developed for seven facial regions. With the exception of the mandible, all injury criteria predicted risk of fracture up to 100% risk (graphical representation of the frontal bone only displayed up to 5000 N). Comparison of the PMHS and FOCUS headform responses shows that the FOCUS headform is biofidelic for all facial locations except the nasal bone. The injury criteria presented herein and the biofidelic response of the FOCUS headform provide Army materiel developers the ability to assess facial injury risk, determine the benefit of potential facial-protection devices, and characterize any residual injury risk due to behind-armor effects or novel threats. Additionally, future work should aim to develop a more robust mandible injury criteria for frontal mandible impacts and develop an injury criteria for lateral mandible impacts. Gender effects, as well as age, should also be investigated for all facial bone regions.

References

Brennan, J. (2013). Head and neck trauma in Iraq and Afghanistan: Different war, different surgery, lessons learned. *Laryngoscope*, *123*(10), 2411-2417.

Brozoski, Frederick T. (2012). Facial Fracture Risk Functions for Assessing the Performance of Improved Face and Eye Protective Equipment. Fort Rucker, AL: United States Army Aeromedical Research Laboratory. Accession No. AD1048503.

Cormier, J., Bisplinghoff, J., & Duma, S. (2008a). Fracture Tolerance Thresholds of Human Facial Bones Subjected to Blunt Impact. Fort Rucker, AL: United States Army Aeromedical Research Laboratory. USAARL Report No. CR-2008-07 (ADB343414).

Cormier, J., Manoogian, S., Bisplinghoff, McNally, C., & Duma, S. (2008b). The use of acoustic emission in facial fracture detection. *Biomedical Sciences Instrumentation, 44*, 147-52.

Cormier, J. (2009). *Epidemiology and Biomechanical Analysis of Facial Fractures* (Dissertation). Virginia Polytechnic Institute and State University, 1-259.

Cormier, J., Manoogian, S., Bisplinghoff, J., Rowson, S., Santago, A., McNally, C., ..., Bolte, J. IV. (2010a). Biomechanical response of the human face and corresponding biofidelity of the FOCUS headform. *SAE International Journal of Passenger Cars—Mechanical Systems, 3*(1), 842-859.

Cormier, J., Manoogian, S., Bisplinghoff, J., Rowson, S., Santago, A., McNally, C., ..., Bolte, J. IV. (2010b). The tolerance of the nasal bone to blunt impact. *Annals of Advances in Automotive Medicine*, *54*, 3-14.

Cormier, J., Manoogian, S., Bisplinghoff, J., Rowson, S., Santago, A., McNally, C., ..., Bolte, J. IV. (2011a). The tolerance of the frontal bone to blunt impact. *Journal of Biomechanical Engineering*, *133*(2), 021004.

Cormier, J., Manoogian, S., Bisplinghoff, J., Rowson, S., Santago, A., McNally, C., ..., Bolte, J. IV. (2011b). The tolerance of the maxilla to blunt impact. *Journal of Biomechanical Engineering*, *133*(6), 064501.

Hale, R.G., Hayes, D.K., Orloff, G., Peterson, K., Powers, D.B., and Mahadevan, S. (2012). “Maxillofacial and Neck Trauma.” *In Combat Casualty Care: Lessons Learned from OEF and OIF.* Lenhart, M.K., Savitsky, E., Eastbridge, B., and Eastridge, B. (Eds.), Government Printing Office.

Haley, J. (1988). Anthropometry and mass distribution for human analogues. Fort Rucker, AL: United States Army Aeromedical Research Laboratory. USAARL Report No. 88-5.

Keller, M.W., Han, P.P., Galarneau, M.R., & Gaball, C.W. (2015) Characteristics of maxillofacial injuries and safety of in-theater facial fracture repair in severe combat trauma. *Military Medicine*, *180*(3), 315-320.

Kennedy EA, Inzana JA, McNally C, Depinet P, Sullenberger KH, Morgan CR, …, Duma SM (2007). Development and validation of a synthetic eye and orbit for estimating the potential for globe rupture due to specific impact conditions. *Stapp Car Crash Journal, 51*, 381-400.

Lessley, D., Crandall, J., Shaw, G., Kent, R., & Funk, J. (2004). A normalization technique for developing corridors from individual subject response. *Society of Automotive Engineers*, 2004-01-0288.

Levine, E., Degutis, L., Pruzinsky, T., Shin, J., & Persing, J.A. (2005). Quality of life and facial trauma: Psychological and body image effects. *Annals of Plastic Surgery*, *54*(5), 502-510.

Lew, T.A., Walker, J.A., Wenke, J.C., Blackbourne, L.H., & Hale, R.G. (2010). Characterization of craniomaxillofacial battle injuries sustained by United States service members in the current conflicts of Iraq and Afghanistan. *Journal of Oral Maxillofacial Surgery*, *68*(1), 3-7.

Owens, B.D., Kragh, J.F., Wenke, J.C., Macaitis, J., Wade, C.E., & Holcomb, J.B. (2008). Combat wounds in operation Iraqi Freedom and operation Enduring Freedom. *Journal of Trauma*, 64(2), 295-9.

Shanahan, D. F., & Shanahan M. O. (1989). Injury in US helicopter crashes October 1979-September 1985. *Journal of Trauma*. *29*, 415-423.

Society of Automotive Engineers (SAE). (1995). *Instrumentation for Impact Test – Part 1 – Electronic Instrumentation* (SAE Report Number J211b). Warrendale, PA. Society of Automotive Engineers.

Acronyms

A-P	Anterior-Posterior
AE	Acoustic Emission
ATD	Anthropomorphic Test Device
CDF	Cumulative Distribution Function
CFC	Corner Frequency Class
CMF	Craniomaxillofacial
FOCUS	Facial and Ocular CountermeasUre for Safety
IC	Interval Censored
NC	Non-Censored
PMHS	Postmortem Human Subject
SAE	Society of Automotive Engineers
USAARL	U.S. Army Aeromedical Research Laboratory

Units

cm	centimeter
fps	frames per second
J	Joule
kg	kilogram
kHz	kilohertz
MHz	megahertz
m	meter
mm	millimeter
N	Newton
lb	pound
s	second
V	volt

Appendix A. Model Parameters for Estimating the Risk of Injury

Table A. Model Parameters for Estimating the Risk of Injury as a Function of the Applied Force and Impacted Facial Region.

Facial Region	Model	Parameter	Estimate	95% Confidence Interval	
				Lower	Upper
Frontal Bone	Non-Censored	Scale	0.00031	0.00041	0.00023
		Shape	1.49	1.08	2.04
	Interval Censored	Scale	0.00024	0.00029	0.00019
		Shape	2.25	1.59	3.18
Nasal Bone	Non-Censored	Scale	0.0013	0.0017	0.0010
		Shape	1.65	1.20	2.26
Maxilla	Non-Censored	Scale	0.0007	0.0009	0.0006
		Shape	2.39	1.73	3.29
Mandible	Non-Censored	Scale	0.0005	0.0009	0.0003
		Shape	2.77	1.23	6.24
Lateral Frontal Bone	Mixed Censored	Scale	0.00032	^	^
		Shape	1.35	^	^
Lateral Nasal Bone	Non-Censored	Scale	0.0071	*	*
		Shape	1.77	*	*
Lateral Zygoma	Non-Censored	Scale	0.00098	*	*
		Shape	1.81	*	*

^The 95% confidence intervals were not calculated.
***The 95% confidence intervals were unable to be determined because the parameter was based on the best fit of the digitally reproduced figure.**

Appendix B. Estimates of Fracture Force

Table B1. Estimates of Fracture Force at discrete Risk of Injury values using a Weibull distribution for Anterior-Posterior Impacts.

	Predicted Fracture Force (N) for Anterior-Posterior Impacts				
Risk (%)	**Frontal - NC**	**Frontal - IC**	**Nasal**	**Maxilla**	**Mandible**
10	713	1533	197	558	888
20	1179	2141	310	763	1164
30	1616	2636	412	929	1379
40	2057	3092	512	1079	NA
50	2523	3542	616	1226	NA
60	3042	4008	730	1378	NA
70	3654	4526	861	1544	NA
80	4440	5150	1027	1744	NA
90	5646	6038	1276	2026	NA
95	6738	6786	1496	2262	NA

Table B2. Estimates of Fracture Force at discrete Risk of Injury values using a Weibull distribution for Lateral Impacts.

	Predicted Fracture Force (N) for Lateral Impacts		
Risk (%)	**Frontal**	**Nasal**	**Zygoma**
10	590	40	295
20	1029	60	446
30	1456	79	578
40	1900	96	704
50	2382	115	834
60	2929	134	973
70	3586	156	1131
80	4446	184	1328
90	5796	226	1618
95	7044	262	1871

Appendix C. Estimates of Fracture Force based on the 95% Confidence Intervals for the Weibull Parameters

Table C. Estimates of Fracture Force at discrete Risk of Injury values based on the 95% Confidence Intervals for the Weibull Parameters.

	Predicted Fracture Force (N) for Anterior-Posterior Impacts				
Risk (%)	**Frontal - NC**	**Frontal - IC**	**Nasal**	**Maxilla**	**Mandible**
10	305-1443	839-2595	91-370	303-842	NA
20	609-2085	1343-3285	169-515	467-1057	NA
30	939-2624	1805-3807	250-634	613-1219	NA
40	1310-3129	2261-4262	337-743	754-1359	NA
50	1739-3633	2739-4691	434-851	899-1491	NA
60	2250-4166	3264-5121	547-962	1057-1624	NA
70	2897-4763	3876-5580	687-1086	1237-1764	NA
80	3791-5492	4652-6113	875-1235	1463-1927	NA
90	5280-6545	5828-6842	1179-1447	1800-2148	NA
95	6737-7446	6876-7433	1468-1625	2095-2327	NA