Federal Aviation Administration

DOT/FAA/AM-21/02
Office of Aerospace Medicine
Washington, DC 20591

List of Occupant Injury Criteria

Gerardo Olivares
Luis Gomez
Armando De Abreu

National Institute for Aviation Research
Wichita State University
Wichita, KS 67260

February 2018

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AM-21/02		

4. Title and Subtitle List of Occupant Injury Criteria	5. Report Date February 2018
	6. Performing Organization Code
7. Author(s) Gerardo Olivares, Luis Gomez, Armando De Abreu	8. Performing Organization Report No.
9. Performing Organization Name and Address National Institute for Aviation Research Wichita State University, 1845 Fairmount St Wichita, KS 67260-0093	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency name and Address Office of Aerospace Medicine Federal Aviation Administration 800 Independence Ave., S.W. Washington, DC 20591	13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplemental Notes	

16. Abstract

This study constitutes a summary literature review of injury criteria currently used by regulatory agencies (aerospace and automotive) worldwide, and presents state-of-the-art injury criteria and associated research for most body regions. The literature review findings have been divided into two categories: state-of-the-art injury criteria and state- of- the- art injury research. The state-of-the-art injury criteria category collects those documents where injury criteria are well defined and includes adequate tolerance limits for the criterion in question. This injury criterion should be measurable or derived from physical test parameters. On the other hand, the papers documented as state-of-the-art injury research include those criteria that were or are currently being developed but do not have well defined limits or cannot be measured from physical test parameters.

The study divides injury criteria into classifications of: head, neck, torso, upper extremities, and lower extremities. Each body region is then divided into sagittal and coronal loading. Sagittal and coronal loading are subdivided into existing-regulatory, state-of-the-art injury criteria, and state-of-the-art injury research according to the previous definitions.

17. Key Words	18. Distribution Statement
Injury Criteria, Head, Neck, Torso, Extremities	Document is available to the public through: http://www.faa.gov/go/oamtechreports/

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	38	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

The authors would like to thank all the Federal Aviation Administration (FAA) personnel that have been involved in this research project. In particular, the authors would like to thank David Moorcroft, Joseph Pellettiere, and Rick Deweese for all their contributions and their valuable input throughout the research.

The authors also acknowledge the contributions of researcher Duane Davis and the graduate research assistants from the National Institute for Aviation Research (NIAR) Computational Mechanics Laboratory: Nathaniel J. Baum and Kishan Indrani.

This work supports the Fire and Cabin Safety Technical Community Representative Group Project: System Level Crashworthiness Injury Criteria and Certification Methodology. The work was accomplished under the Wichita State University Cooperative Agreement 12-C-AM-WISU, Amendment 056.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AUROC	Area under receiving operating characteristic (ROC) curve
BRIC	Kinematic rotational brain injury criterion
AIS	Abbreviated injury scale
ATD	Anthropomorphic test device
BC	Blunt criterion
BrIC	Brain injury criterion
C_f	Contribution factor
C_{max}	Maximum chest deflection
CFR	Code of federal regulations
CP	Combined probability of concussion
CSDM	Cumulative strain damage measure
CSF	Cerebral spinal fluid
CTI	Combined thoracic injury criterion
d_1	Maximal deflection caused by localized loading
DAI	Diffuse axonal injury
dD	Differential deflection
d_d	Maximal deflection caused by the distributed loading
d_{eq}	Equivalent deflection
Ds	Sternal deflection
ECE	Economic Commission for Europe
FAA	Federal Aviation Administration
FE	Finite Element
FEA	Finite Element Analysis
FFC	Femur force criterion
fn	Normalization factor
GSI	Gadd severity index
HIC	Head injury criterion
HIC36	Head injury criterion in a 36ms interval
HIP	Head injury power
IARV	Injury assessment reference value
IIHS	Insurance Institute for Highway Safety
IV-NIC	Intervertebral neck injury criterion
KTH	Knee-thigh-hip
Lc	Characteristic length
LIN	Linear accelerations
LNL-index	Lower neck load index
MANIC(Gy)	Multi-axial neck injury criterion
MIX	Mix criterion
mTBI	Mild traumatic brain injury
N/A	Not Applicable
NCAP	New car assessment program
NDC	Neck displacement criterion
NHTSA	National Highway Traffic Safety Administration
NIAR	National Institute for Aviation Research
NIC	Neck injury criterion
NII	Neck injury index
NII_{PMHS}	Adaptation of NII based on PMHS tests

N_{ij}	Neck injury criterion for frontal impact
N_{km}	Neck protection criterion
OC	Occipital condyle
PCS	Principal Component score
PMHS	Post Mortem Human Subject
PRHIC	Power rotational head injury criterion
RIC	Rotational injury criterion
ROC	Receiver operating characteristic
ROT	Rotational accelerations
SDH	Subdural hematoma
SFC	Skull fracture correlate
SSD	Sum of shearing displacements
T1-vertebra	First thoracic vertebra
TBI	Traumatic brain injury
TCFC	Tibia compression force criterion
ThCC	Thoracic compression criterion
TI	Tibia index
TTI	Thoracic trauma index
ULP	Universit´e Louis Pasteur
VC	Viscous criterion
VM	Von-Mises
WAD	Whiplash associated disorder
WIC	Whiplash injury criterion

LIST OF OCCUPANT INJURY CRITERIA

INTRODUCTION

The Federal Aviation Administration (FAA) defines the requirements for occupant protection during emergency landing dynamic conditions in 14 Code of Federal Regulation (CFR) Parts §2x.562. Parts §2x.785 also mentions that the occupant should not suffer serious injury in an emergency landing condition as specified in 2x.562. These CFRs apply to all seats regardless of orientation. However, other occupant protection requirements are usually imposed on side and oblique-facing seats. The current safety criteria specified in these CFRs only include head, pelvis, and femur loading (Part 25 only). The current report includes a comprehensive list of regulatory and state-of-the-art injury criteria for most body regions. These can aid in identifying new guidelines for occupant safety under sagittal and/or coronal loading. This report does not encompass all injury criteria available but it is meant to provide some of the state-of-the-art injury criteria and research publicly available.

The three anatomical body-plane regions are comprised of the sagittal, coronal, and transverse plane. Figure 1 highlights the three anatomical planes. Sagittal loading typically occurs during a frontal impact (forward and aft-facing seats). Motion in the coronal plane occurs when the occupant goes side-to-side. This typically occurs in a side impact (for a forward-facing seat) or when the occupant is seated in a side-facing seat (for a fore-aft crash). Loading due to a vertical impact occurs in both the sagittal and coronal planes.

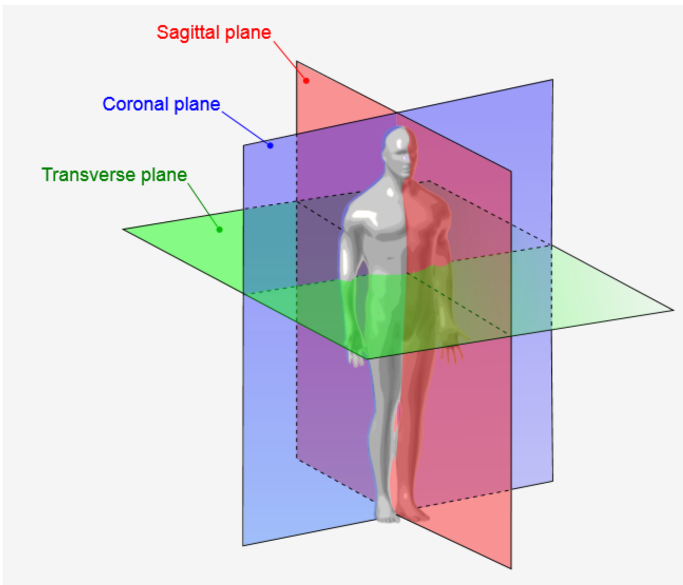

Figure 1. Anatomical Planes [1]

The literature review findings have been divided into three categories: regulatory, state-of-the-art injury criteria, and state-of-the-art injury research. Regulatory injury criteria are those currently used to assess occupant injury levels such as the Head Injury Criteria (HIC) in 14 CFR Part 25.562. The state-of-the-art injury criteria category collects those documents where injury criteria are well defined and includes adequate tolerance limits for the criterion in question. This injury criterion should be measurable or derived from physical test parameters. On the other hand, the papers documented as state-of-the-art injury research include those criteria that were or are currently being developed but do not have well defined limits or cannot be measured from physical test parameters (i.e. Von-Mises stress of a specific part of the brain). Criteria applicable to vertical loading were only included for the lumbar spine.

The results are organized by body region: head, neck, torso, upper extremities, and lower extremities. Each body region is then divided into sagittal and coronal loading. Sagittal and coronal loading are subdivided into existing-regulatory, state-of-the-art injury criteria, and state-of-the-art injury research according to the previous definitions. The nomenclature for each region is comprised of four variables. The first variable identifies the body region, i.e., H for the head, N for the neck, etc. The second variable specifies the type of impact injury, such as penetrating (P) or blunt (B). The third variable is either one or two lower case letters that identify the type of criterion; regulatory (r), state-of-the-art injury criterion (ac), or state-of-the-art injury research (ar). The last variable is a numerical value to keep track of the criteria within the groups and subgroups. Figure 2 shows an example of one of the cases of the head nomenclature.

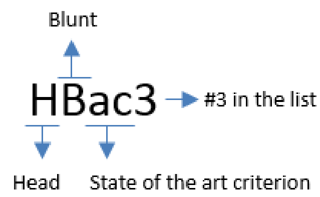

Figure 2. Nomenclature example

INJURY CRITERIA FOR THE HEAD

SAGITTAL LOADING

Regulatory

Table 1 provides a summary of blunt injury criteria for the head currently in use by regulatory agencies.

Table 1. Injury criteria for the head under blunt sagittal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
HBr1	HIC HIC = 390 to 1000 (depending on version and regulation)	FAA [2] NHTSA [3] ECE [4] Japan NCAP [5] IIHS [6] Euro NCAP [7]
HBr2	Deceleration of head form cannot exceed 80g for more than 3ms	NHTSA [3] ECE [4] Euro NCAP [7]

Table 2 provides a summary of penetrating injury criteria for the head currently in use by regulatory agencies.

Table 2. Injury criteria for the head under penetrating sagittal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
HPr1	Areas of contact free of protrusions or sharp edges	FAA [8] NHTSA [9]

State-of-the-Art Injury Criteria

Table 3 provides a summary of sagittal state-of-the-art injury criteria for the head.

Table 3. Injury criteria for the head under blunt sagittal loading – state-of-the-art injury criteria

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
HBac1	Linear combination of HIC_{36} and angular velocity [10]	Strain < $0.004718\Delta\omega + 0.000224HIC_{36}$	• Strain calculated from FEA and derived a linear combination relating angular velocity and HIC to strain • Surface plot shown in figure 18, pg. 18 of [10]	FEA
HBac2	BRIC [11]	$BRIC = \omega_{max}/\omega_{cr}+\alpha_{max}/\alpha_{cr}$ Linearized CSDM and HIC were used to obtain risk curves related to BRIC (pg. 5-6 of [11]) BRIC is roughly 1 for 50% AIS 3+	• Authors note that BRIC is not an "ultimate" head injury criterion that captures all possible brain injuries and skull fractures, but rather a correlation to TBI with head rotation being a primary injury mechanism. Also, They mention that using HIC and BRIC together might offer better performance	ATD and FEA
HBac3	BrIC [12]	BrIC = sqrt((ω_x/ω_{xc})^2 + (ω_y/ω_{yc})^2 + (ω_z/ω_{zc})^2) BrIC = 2 for 50% AIS3+ risk (See curves pg. 310 of [12])	• Similar to BRIC. However, it is not known whether BrIC is meant to be a replacement of BRIC • Original development of BrIC cited BrIC = 1.08 for 50% AIS3+ risk [13]	ATD and FEA
HBac4	RIC [14]	RIC_{36} = 1.03x10^7 for 50% risk of MTBI $RIC = \left[(t_2-t_1)\left(\frac{1}{(t_2-t_1)}\right)\int_{t_1}^{t_2}\alpha(t)dt)^{2.5}\right]_{max}$	• Authors propose to use RIC, PRHIC, and HIC in conjunction	HIC

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
HBac5	PRHIC [14]	$PRHIC_{36}$ = 8.70x10^5 for 50% risk of MTBI $PRHIC = \left[(t_2 - t_1)\left(\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} HIP\_rot\,dt\right)^{2.5}\right]_{max}$	• Authors propose to use RIC, PRHIC, and HIC in conjunction	HIC and HIP
HBac6	Blunt criterion (BC) for skull fracture [15]	F = 5970 N for 50% risk BC = 1.61 for 50% risk Strain = 0.51% for 50% risk $BC = ln\frac{0.5mV^2}{M^{1/3}TD}$	• *m* is the mass of the projectile, *V* the velocity of the projectile, *M* the mass of the struck individual, *T* the combined thickness of the soft tissue and skull at the impact location, and *D* the diameter of the projectile	PMHS
HBac7	Skull Fracture Correlate [16][17]	$SFC = A_{HIC} = \Delta V_{HIC}/\Delta T_{HIC}$ SFC < 120g for skull fracture probability less than 15%		PMHS and ATD
HBac8	Combined probability of concussion (CP) [18]	CP contours are provided in figure 2 of [18] CP = 0.5 (i.e. a ≈ 120g and α ≈ 7000 rads/s^2) for 50% risk $CP = \frac{1}{1+e^{-(\beta_0+\beta_1 a+\beta_2 \propto+\beta_3 a\alpha)}}$	• A concussion risk function was developed from football players' dataset using a multivariate logistic regression analysis • *β0, β1*, and *β2* are regression coefficients, *a* is peak linear acceleration, *α* is peak rotational acceleration	Human dataset
HBac9	Injury risk vs. ΔV [19]	See figures 2 and 4 in [19] for AIS 2+ curves in various regions ΔV ≈ 95 km/h for 50% head injury risk belted AIS 2+	• Provides injury risk (AIS 2+ vs ΔV) for most regions of the body for belted and unbelted cases	Human dataset

State-of-the-Art Injury Research

Table 4 provides a summary of sagittal state-of-the-art injury research.

Table 4. Injury criteria for the head under blunt sagittal loading – state-of-the-art injury research

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
HBar1	Shear stress [20]	7.8 kPa for 50% risk of MTBI	• Reference also provides angular velocity risk curves	ATD and FEA
HBar2	VM strain, VM stress, and First principal strain for DAI [21] CSF pressure for SDH [21] Skull strain energy for skull fracture [21]	VM strain = 25% Mild DAI, 35% Severe DAI First strain = 31% Mild DAI, 40% Severe DAI VM Stress(kPa) = 26 Mild DAI, 33 Severe DAI CSF pressure = -135 kPa for SDH Skull strain energy = 865 mJ for skull fracture All limits are for 50% risk	• Injury metrics were taken from the ULP FEM	FEA
HBar3	Axonal strain [22]	Axonal strain = 0.1565 for 50% risk of DAI	• Seems to have good correlation with DAI; axonal strain AUROC=0.988, axonal strain rate AUROC=0.889	FEA
HBar4	Principal component score [23]	PCS = 10((.4718*sGSI + .4742*sHIC + .4336*sLIN + .2164*sROT) + 2) Where sX=(X-mean(X))/(SD(X))	• Combination of other injury criteria values in one equation • PCS can be multiplied by a coefficient to adjust for impact location	Other injury metrics

CORONAL LOADING

Regulatory

Table 5 provides a summary of blunt head injury criteria currently in use by regulatory agencies.

Table 5. Injury criteria for the head under blunt coronal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
HBr3	HIC HIC = 390 to 1000 (depending on version and regulation)	FAA [2] NHTSA [24] ECE [25] Japan NCAP [5] IIHS [26] Euro NCAP [7]
HBr4	Resultant acceleration of head form cannot exceed 72g for more than 3 ms	Euro NCAP [7]
HBr5	Contact surface covered with ≥ 2 in padding (recommendation)	FAA (Special Condition) [27]

Table 6 provides a summary of penetrating head injury criteria currently in use by regulatory agencies.

Table 6. Injury criteria for the head under penetrating coronal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
HPr2	Areas of contact free of protrusions or sharp edges	FAA [8] NHTSA [9]

State-of-the-Art Injury Criteria

Table 7 provides a summary of coronal state-of-the-art injury criteria.

Table 7. Injury criteria for the head under blunt coronal loading – state-of-the-art injury criteria

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
HBac10	Linear combination of HIC_{36} and angular velocity [10]	Strain < $0.004718\Delta\omega + 0.000224HIC_{36}$	• Strain calculated from FEA and derived a linear combination relating angular velocity and HIC to strain • Surface plot shown in figure 18, pg. 18 of [10]	FEA

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
HBac11	BRIC [11]	BRIC = $\omega_{max}/\omega_{cr}+\alpha_{max}/\alpha_{cr}$ Linearized CSDM and HIC were used to obtain risk curves related to BRIC (pg. 5-6 of [11]) BRIC ≈ 1 for 50% AIS 3+	• Authors note that BRIC is not an "ultimate" head injury criterion that captures all possible brain injuries and skull fractures, but rather a correlation to TBI with head rotation being a primary injury mechanism. Also, they mention that using HIC and BRIC together might offer better performance	ATD and FEA
HBac12	BrIC [12]	BrIC=sqrt((ω_x/ω_{xc})^2+(ω_y/ω_{yc})^2+(ω_z/ω_{zc})^2) BrIC = 2 for 50% AIS3+ risk (See curves pg. 310 of [12])	• Similar to BRIC. However, it is not known whether BrIC is meant to be a replacement of BRIC • Original development of BrIC cited BrIC = 1.08 for 50% AIS3+ risk [13]	ATD and FEA
HBac13	RIC [14]	RIC36 = 1.03x10^7 for 50% risk of MTBI RIC= $[(t_2-t_1)\left(\frac{1}{(t_2-t_1)}\right)\int_{t_1}^{t_2}\alpha(t)dt)^{2.5}]_{max}$	• Authors propose to use RIC, PRHIC, and HIC in conjunction	HIC
HBac14	PRHIC [14]	PRHIC36 = 8.70x10^5 for 50% risk of MTBI PRHIC= $[(t_2-t_1)\left(\frac{1}{(t_2-t_1)}\right)\int_{t_1}^{t_2}\text{HIP\_rot}dt)^{2.5}]_{max}$	• Authors propose to use RIC, PRHIC, and HIC in conjunction	HIC and HIP
HBac15	Peak contact force and work [28]	Contact F = 1800 N for 50% Face fracture (AIS1+) Contact F = 4700 N for 50% vault fracture (AIS2+)	• Risk curves vs. deformation work given on pg. 7 [28]	PMHS
HBac16	Blunt criterion (BC) for skull fracture [15]	F = 5970 N for 50% risk BC = 1.61 for 50% risk Strain = 0.51% for 50% risk $BC = ln\frac{0.5mV^2}{M^{1/3}TD}$	• *m* is the mass of the projectile, *V* the velocity of the projectile, *M* the mass of the struck individual, *T* the combined thickness of the soft tissue and skull at the impact location, and *D* the diameter of the projectile	PMHS

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
HBac17	Skull Fracture Correlate [16][17]	$SFC = A_{HIC} = \Delta V_{HIC}/\Delta T_{HIC}$ SFC < 120g for skull fracture probability less than 15%		PMHS and ATD
HBac18	Combined probability of concussion (CP) [18]	CP contours are provided in fig. 2 of [18] CP = 0.5 (i.e. a ≈ 120g and α ≈ 7000 rads/s^2) for 50% risk $CP = \frac{1}{1 + e^{-(\beta_0+\beta_1 a+\beta_2 \propto+\beta_3 a\alpha)}}$	• A concussion risk function was developed from football players' dataset using a multivariate logistic regression analysis • *β0, β1*, and *β2* are regression coefficients, *a* is peak linear acceleration, *α* is peak rotational acceleration	Human dataset

State-of-the-Art Injury Research

Table 8 provides a summary of coronal state-of-the-art injury research.

Table 8. Injury criteria for the head under blunt coronal loading – state-of-the-art injury research

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
HBar5	Shear stress [19]	7.8 kPa for 50% risk of MTBI	• Reference also provides angular velocity risk curves	ATD and FEA
HBar6	VM strain, VM stress, and First principal strain for DAI [21] CSF pressure for SDH [21] Skull strain energy for skull fracture [21]	VM strain = 25% Mild DAI, 35% Severe DAI First strain = 31% Mild DAI, 40% Severe DAI VM Stress(kPa) = 26 Mild DAI, 33 Severe DAI CSF pressure = -135 kPa for SDH Skull strain energy = 865 mJ for skull fracture	• Injury metrics were taken from the ULP FEM	FEA

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
		All limits are for 50% risk		
HBar7	Axonal strain [22]	Axonal strain = 0.1565 for 50% risk of DAI	• Seems to have good correlation with DAI; axonal strain AUROC = 0.988, axonal strain rate AUROC = 0.889	FEA
HBar8	Principal component score [23]	PCS = 10((.4718*sGSI + .4742*sHIC + .4336*sLIN + .2164*sROT) + 2) Where sX = (X-mean(X))/(SD(X))	• Combination of other injury criteria values in one equation • PCS can be multiplied by a coefficient to adjust for impact location	Other injury metrics

INJURY CRITERIA FOR THE NECK

SAGITTAL LOADING

Regulatory

Table 9 provides a summary of blunt neck injury criteria currently in use by regulatory agencies.

Table 9. Injury criteria for the neck under blunt sagittal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
NBr1	Peak tension, compression, and shear (compression applies to NHTSA and IIHS only and shear applies to Euro and Japan NCAP only)	NHTSA [3] Japan NCAP [5] IIHS [6] Euro NCAP [7]

Criterion Nomenclature	Injury Criterion	Agencies
NBr2	N_{ij}	NHTSA [3] IIHS [6] FAA (Special Condition) [40][1]
NBr3	NII	ISO 13232-5 [29]
NBr4	NIC	ECE [4] Euro NCAP [7]
NBr5	Bending moment	ECE [4] Japan NCAP [5] Euro NCAP [7]
NBr6	N_{km} (whiplash)	Euro NCAP [7]
NBr7	Head rebound velocity (whiplash)	Euro NCAP [7]
NBr8	T1-vertebra x-acceleration (whiplash)	Euro NCAP [7]
NBr9	Head restraint contact time (whiplash)	Euro NCAP [7]
NBr10	Max seat deflection (for high pulse) (whiplash)	Euro NCAP [7]

Table 10 provides a summary of Penetrating Neck Injury Sagittal Loading - Regulatory.

Table 10. Injury criteria for the neck under penetrating sagittal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
NPr1	Areas of contact free of protrusions or sharp edges	FAA [8] NHTSA [9]

State-of-the-Art Injury Criteria

Table 11 provides a summary of Neck state-of-the-art injury criteria.

Table 11. Injury criteria for the neck under blunt sagittal loading – state-of-the-art injury criteria

[1] N_{ij} has been applied to oblique seats by FAA Special Condition. While these seats are considered side-facing, N_{ij} evaluates sagittal loading, not coronal loading.

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
NBac1	MIX [30]	MIX= $\sqrt{\left(\frac{NIC_{max}}{NIC_{av}}\right)^2 + \left(\frac{N_{km}}{N_{av}}\right)^2}$ MIX ≈ 4.1 for 50% risk of AIS1+ with symptoms > 1 month	• Risk curve shown in figure 16 of [30]	N_{km} and NIC_{max}
NBac2	NII_{PMHS} [31]	NII_{PMHS}= $max\left(\left(\left(\left(\left(\frac{F_C}{F_{CC}}\right)^2 + \left(\frac{F_T}{F_{TC}}\right)^2 + \left(\left(\frac{Mx}{Fz_{crit}}\right)^2 + \left(\frac{Mext}{My_{crit}}\right)^2\right)^{1/2}\right)^2 + \left(\frac{Mflx}{Mz_{crit}}\right)^2\right)^{1/2}, 1.77\left(\frac{Fc}{F_{cc}} + \frac{F_T}{F_{TC}}\right)\right)$ NII_{PMHS} = 1.86 for 50% risk of AIS3+	• Adaptation of NII	NII and PMHS
NBac3	MANIC(-Gx) [58]	N_{ij}	• Modified risk curves for AIS2+ and AIS3+ provided [58]	Human dataset
NBac4	Modified N_{ij} [33]	$Nij = \frac{Fz}{3880\ N} + \frac{\sqrt{My^2 + Mx^2}}{155\ Nm}$ N_{ij} < 1 limit	• Assumed similar injury characteristic for flexion and lateral bending	Nij
NBac5	Sum of the shearing displacement (SSD) at each intervertebral level [34]	$SSD = \sum_{i=1}^{7} \lvert C_i - C_{i+1} \rvert dx$ Where C are the vertebrae shearing displacement SSD ≈ 4.75 mm for 50% risk of WAD3+	• Criterion does not seem to correlate very well with the data • Risk curves for WAD1+, 2+, and 3+ shown in figure 27 of [34] • Criterion for whiplash injury	FEA

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
NBac6	NDC [35]	θoc < 50°, xoc-t1 < 70 mm and zoc-t1 < -35 mm for acceptable level (Hybrid III). θoc is the OC rotation, xoc-t1 and zoc-t1 are the displacements of T1 relative to OC	• Guidelines are dependent on dummy used. Hybrid III and BioRID P3 guidelines were defined on the study • See figures 7, 8 and tables VI, VII of [35] for the proposed guidelines	Human subjects and ATD
NBac7	Injury risk vs ΔV [19]	See figures 2 and 4 in [19] for AIS 2+ curves in various regions ΔV ≈ 97 km/h for 50% neck/spine injury risk belted AIS 2+	• Provides injury risk (AIS 2+ vs ΔV) for most regions of the body for belted and unbelted cases	Human dataset

State-of-the-Art Injury Research

Table 12 provides a summary of sagittal state-of-the-art injury research.

Table 12. Injury criteria for the neck under blunt sagittal loading – state-of-the-art injury research

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
NBar1	ΔV [36]	ΔV=2.3 m/s for 15% risk of serious injury ΔV=4.2 m/s for 50% risk of serious injury	• Authors note that more data is needed in the 2-4 m/s head velocity	PMHS
NBar2	WIC [37]	WIC = Myoc-Mlw Myoc = moment about OC Mlw = moment measured at the T1 load cell	• No tolerance limits provided • Criterion for whiplash injury	ATD
NBar3	LNL – Index [38]	$LNL = \left\lvert\frac{\sqrt{My_{lower}{}^2+Mx_{lower}{}^2}}{C_{moment}}\right\rvert + \left\lvert\frac{\sqrt{Fx_{lower}{}^2+Fy_{lower}{}^2}}{C_{shear}}\right\rvert + \left\lvert\frac{Fz_{lower}}{C_{tension}}\right\rvert$	• Lower moments measured at a different vertebra than the one intended (T1) • No tolerance limits provided	ATD

CORONAL LOADING

Regulatory

Table 13 provides a summary of blunt neck injury criteria currently in use by regulatory agencies.

Table 13. Injury criteria for the neck under blunt coronal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
NBr11	Peak tension, compression, and shear (shear applies to FAA only)	FAA [39] IIHS [26]
NBr12	Bending moment	FAA [39]
NBr13	Rotation of head relative to torso (oblique seat)	FAA (Special Condition) [40]
NBr14	No concentrated loading from contact (oblique seat)	FAA (Special Condition) [40]
NBr15	Contact surface covered with ≥ 2 in padding (recommendation)	FAA (Special Condition) [27]

Table 14 provides a summary of Penetrating Neck Injury Coronal Loading Regulatory.

Table 14. Injury criteria for the neck under penetrating coronal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
NPr2	Areas of contact free of protrusions or sharp edges	FAA [8] NHTSA [9]

State-of-the-Art Injury Criteria

Table 15 provides a summary of Neck state-of-the-art injury criteria.

Table 15. Injury criteria for the neck under blunt coronal loading – state-of-the-art injury criteria

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
NBac8	MANIC(Gy) [32]	MANIC(Gy)= $\sqrt{\left(\frac{Fx}{Fx_{crit}}\right)^2 + \left(\frac{Fy}{Fy_{crit}}\right)^2 + \left(\frac{Fz}{Fz_{crit}}\right)^2 + \left(\frac{My}{My_{crit}}\right)^2 + \left(\frac{Mz}{Mz_{crit}}\right)^2}$ MANIC(Gy) = 0.473 for 5% risk of AIS 2+	• Risk curves for AIS2+ and AIS3+ provided in figure 5, pg.160 of [32]	Human dataset
NBac9	IV-NIC [41]	$\mathrm{IV - NICi, j(t)} = \frac{\theta_{dynamic, \ i,j}(t)}{\theta_{physiological, \ i,j}}$ IV-NIC injurious threshold = 1.5-4.0 Depending on intervertebral level	• Does not provide risk curves	PMHS
NBac10	Modified Nij [33]	$\mathrm{Nij} = \frac{Fz}{3880\ N} + \frac{\sqrt{My^2 + Mx^2}}{155\ Nm}$ Nij < 1 limit	• Assumed similar injury characteristic for flexion and lateral bending	Nij

State-of-the-Art Injury Research

Table 16 provides a summary of coronal state-of-the-art injury research.

Table 16. Injury criteria for the neck under blunt coronal loading – state-of-the-art injury research

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
NBar4	LNL – Index [38]	$LNL = \left\lvert\frac{\sqrt{My_{lower}{}^2+Mx_{lower}{}^2}}{C_{moment}}\right\rvert + \left\lvert\frac{\sqrt{Fx_{lower}{}^2+Fy_{lower}{}^2}}{C_{shear}}\right\rvert + \left\lvert\frac{Fz_{lower}}{C_{tension}}\right\rvert$	• Lower moments measured at a different vertebra than the one intended (T1) • No tolerance limits provided	ATD

INJURY CRITERIA FOR THE TORSO

SAGITTAL LOADING

Regulatory

Table 17 provides a summary of blunt thorax injury criteria currently in use by regulatory agencies.

Table 17. Injury criteria for the torso under blunt sagittal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
TBr1	Acceleration of thoracic instrumentation cannot exceed 60g for more than 3 ms	NHTSA [3] Japan NCAP [5] IIHS [6]
TBr2	Compressive deflection of the sternum relative to the spine (ThCC)	NHTSA [3] ECE [4] IIHS [6] Euro NCAP [7]
TBr3	Chest deflection	Japan NCAP [5]
TBr4	Viscous Criterion (VC)	ECE [4] IIHS [6] Euro NCAP [7]
TBr5	Sternum deflection rate	IIHS [6]
TBr6	No submarining	FAA [2] Japan NCAP [5]
TBr7	Load in shoulder harness straps	FAA [2]

Criterion Nomenclature	Injury Criterion	Agencies
TBr8	Lumbar load	FAA [2]

Table 18 provides a summary of Penetrating Thoracic Injury Sagittal Loading in use by regulatory agencies.

Table 18. Injury criteria for the torso under penetrating sagittal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
TPr1	Areas of contact free of protrusions or sharp edges	FAA [8] NHTSA [9]

State-of-the-Art Injury Criteria

Table 19 provides a summary of Thorax state-of-the-art injury criteria.

Table 19. Injury criteria for the torso under blunt sagittal loading – state-of-the-art injury criteria

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
TBac1	Combined deflection (Dc) [42]	Dc = Ds + Cf[(dD - Lc) + |(dD - Lc)|] Dc < 65 mm for 50% risk of 6+ rib fracture	• Risk curves shown in figures 12 of [42] • Moderate restraint dependency	FEA
TBac2	Maximum chest deflection (C_{max}) [43]	C_{max} ~ 37% for 50% risk of 6+ rib fracture (60 year old male)	• Risk curves shown in figures 4-5 of [43] • Age sensitive	PMHS and FEA
TBac3	Equivalent deflection (d_{eq}) [44]	$d_{eq}(t) = (d_1\text{^}2(t) + f_n d_d(t)\text{^}2)\text{^}(1/2)$ $d_{eq} \approx 32$ mm for 50% AIS3+ risk	• ASI3+ risk curve in figure 22, pg. 338 of [44]. • In addition, it presents belt only, airbag only, combined, and all restraints risk curves for other criteria (VC, CTI, sternum deflection). • Risk curves were modified to include age effects	FEA, PMHS, and ATD
TBac4	Injury risk vs ΔV [19]	See figures 2 and 4 in [19] for AIS 2+ curves in various regions	• Provides injury risk (AIS 2+ vs ΔV) for most regions of the body for belted and unbelted cases	Human dataset

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
		ΔV ≈ 80 km/h for 50% thorax injury risk belted AIS 2+		
TBac5	Eiband [59]	See figure 3 in [59]	• Human volunteers tolerated 10 G for 0.1 seconds and 15 G for 0.05 seconds	Human volunteer and animal data
TBac6	DRI [60]	See details in [60]	• DRI of 19 is approximately a 9% risk of a detectable spinal injury	Human dataset

State-of-the-Art Injury Research

Table 20 provides a summary of sagittal state-of-the-art injury research.

Table 20. Blunt Lower Extremities State-of-the-Art Research Sagittal Loading

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
TBar1	Pelvis Loads [45]	-	• A literature review itself • Provides tolerance limits from other papers	N/A
TBar2	Pelvis Loads [46]	Peak axial force injury tolerance 6.1 kN (AIS 2+)	-	PMHS
TBar3	Hip joint load [47]	Neutral posture fracture tolerance ~5.7-6.1 kN	• Tolerance load decreases 1.8% per degree of adduction & 1% per degree of flexion	PMHS

CORONAL LOADING

Regulatory

Table 21 provides a summary of blunt thorax injury criteria currently in use by regulatory agencies.

Table 21. Injury criteria for the torso under blunt coronal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
TBr9	Rib deflection	NHTSA [24] FAA [39] IIHS [26] ECE [25] Euro NCAP [7]
TBr10	Chest deflection	Japan NCAP [5]
TBr11	Viscous Criterion (VC)	ECE [25] Euro NCAP [7] IIHS [26]
TBr12	Thoracic Trauma Index (TTI)	NHTSA [24] FAA[48]
TBr13	Abdominal forces	NHTSA [24] FAA [39] ECE [25] Japan NCAP [5]
TBr14	Rib deflection rate	IIHS [26]
TBr15	Lateral flexion < 40°	FAA [39]
TBr16	Rearward acceleration cannot exceed 20g for more than 3 ms (Oblique seats)	FAA (Special Condition) [40]
TBr17	Contact surface covered with ≥ 2in padding (recommendation)	FAA (Special Condition) [27]
TBr18	Load in shoulder harness straps	FAA [2]
TBr19	Abdomen lateral compression	Euro NCAP [7]
TBr20	Lumbar load	FAA [2]
TBr21	Pelvic acceleration	FAA [8]
TBr22	Pubic symphysis force	FAA [39] NHTSA [24] ECE [25] Euro NCAP [7]

Criterion Nomenclature	Injury Criterion	Agencies
		Japan NCAP [5]
TBr23	Load bearing portion of pelvis shall remain on the seat cushion (edge)	FAA [39]
TBr24	Resultant lower spine acceleration	NHTSA [24]
TBr25	Acetabular and iliac pelvic forces	NHTSA [24] IIHS [26]
TBr26	Shoulders remain aligned with the hips	FAA (Special Condition) [40]

Table 22 provides a summary of Penetrating Thorax Injury Coronal Loading in use by regulatory agencies.

Table 22. Injury criteria for the torso under penetrating coronal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
TPr2	Areas of contact free of protrusions or sharp edges	FAA [8] NHTSA [9]

State-of-the-Art Injury Criteria

None reported.

State-of-the-Art Injury Research

Table 23 provides a summary of sagittal state-of-the-art injury research.

Table 23. Injury criteria for the torso under blunt coronal loading – state-of-the-art injury research

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
TBar4	Loading corridors [49]	Deflection, accelerations, and force corridors shown in figures 7-8 of [49]	• Several tests with different wall configuration (i.e. padded, rigid, and offset) • Small females in side impacts	PMHS

INJURY CRITERIA FOR THE UPPER EXTREMITIES

SAGITTAL LOADING

Regulatory

Table 24 provides a summary of blunt upper extremities injury criteria currently in use by regulatory agencies.

Table 24. Injury criteria for the upper extremities under blunt sagittal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
UBr1	Humerus mid-shaft bending moment (upper arm)	IARVs [50]
UBr2	Ulna mid-shaft bending moment (forearm)	IARVs [50]

State-of-the-Art Injury Criteria

Table 25 provides a summary of sagittal state-of-the-art injury criteria.

Table 25. Injury criteria for the upper extremities under blunt sagittal loading – state-of-the-art injury criteria

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
UBac1	Forearm Bending Tolerance [51]	Mean fracture force: 1860 N Mean bending moment to failure: 94 ± 41 Nm See figure 5 of [51] for graphed limits	• Slightly lower limit values at lower velocity tests, but not statistically different.	PMHS
UBac2	Humerus Limits [52]	50th percentile limits: Fx = Fy = 2.5 kN Mx = My = 230 Nm	-	PMHS
UBac3	Forearm Bending Tolerance [53]	At 3 m/s: Fracture Force 1386 ± 198 N Bending moment 88.9 ± 12.6 Nm	-	PMHS
UBac4	Injury risk vs ΔV [19]	See figures 2 and 4 in [19] for AIS 2+ curves in various regions ΔV ≈ 85 km/h for 50% upper extremities injury risk belted AIS 2+	• Provides injury risk (AIS 2+ vs ΔV) for most regions of the body for belted and unbelted cases	Human dataset

State-of-the-Art Injury Research

None reported.

CORONAL LOADING

Regulatory

Table 26 provides a summary of blunt upper extremities injury criteria currently in use by regulatory agencies.

Table 26. Injury criteria for the upper extremities under blunt coronal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies

UBr3	Shoulder deflection	IIHS [26] IARVs [50]
UBr4	Lateral shoulder load	Euro NCAP [7] IARVs [50]
UBr5	Humerus mid-shaft bending moment (upper arm)	IARVs [50]
UBr6	Ulna mid-shaft bending moment (forearm)	IARVs [50]

State-of-the-Art Injury Criteria

Table 27 provides a summary of Upper Extremities state-of-the-art injury criteria.

Table 27. Injury criteria for the upper extremities under blunt coronal loading – state-of-the-art injury criteria

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
UBac5	Forearm Bending Tolerance [51]	Mean fracture force: 1860 N Mean bending moment to failure: 94 ± 41 Nm See figure 5 of [51] for graphed limits	• Slightly lower limit values at lower velocity tests, but not statistically different.	PMHS
UBac6	Humerus Limits [52]	50th percentile limits: Fx = Fy = 2.5 kN Mx = My = 230 Nm	-	PMHS
UBac7	Forearm Bending Tolerance [53]	At 3 m/s: Fracture Force 1386 ± 198 N Bending moment 88.9 ± 12.6 Nm	-	PMHS

State-of-the-Art Injury Research

None reported.

INJURY CRITERIA FOR THE LOWER EXTREMITIES

SAGITTAL LOADING

Regulatory

Table 28 provides a summary of blunt lower extremities injury criteria currently in use by regulatory agencies.

Table 28. Injury criteria for the lower extremities under blunt sagittal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
LBr1	Femur force criterion (FFC)	NHTSA [3] ECE [4] Euro NCAP [7] Japan NCAP IIHS [6] FAA [2]
LBr2	Tibia compression force criterion (TCFC)	ECE [4] Euro NCAP [7] IIHS [6]
LBr3	Tibia index (TI)	ECE [4] Euro NCAP [7] Japan NCAP [5] IIHS [6]
LBr4	Movement of sliding knee joints (tibia-femur displacement)	ECE [4] Euro NCAP [7] IIHS [6]
LBr5	Pedal rearward displacement	Euro NCAP [7] Japan NCAP [5]
LBr6	Foot acceleration	IIHS [6]
LBr7	KTH criterion	IIHS [6]

State-of-the-Art Injury Criteria

Table 29 provides a summary of sagittal state-of-the-art injury criteria.

Table 29. Injury criteria for the lower extremities under blunt sagittal loading – state-of-the-art injury criteria

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
LBac1	Plantar foot load [54]	9.1 kN for 50% risk of any foot-ankle injury (50 years) Other probability levels provided in tables 2-4 of [54].	• Provides risk curves for 3 Groups of fracture; all foot-ankle, any calcaneus, and any tibia injury	PMHS
LBac2	Plantar flexed-foot load [55]	3.3 kN for 50% risk of foot injury See table 3 and figures 6-8 of [55] for other thresholds	-	PMHS
LBac3	Ankle malleolus injury criterion [56]	50 Nm dorsiflexion for 25% risk of ankle malleolus injury 33 Nm eversion for 25% risk of Ankle malleolus injury	-	Human dataset
LBac4	Injury risk vs ΔV [19]	See figures 2 and 4 in [19] for AIS 2+ curves in various regions ΔV ≈ 75 km/h for 50% lower extremities injury risk belted AIS 2+	• Provides injury risk (AIS 2+ vs ΔV) for most regions of the body for belted and unbelted cases	Human dataset

State-of-the-Art Injury Research

None reported.

CORONAL LOADING

Regulatory

Table 30 provides a summary of blunt lower extremities injury criteria currently in use by regulatory agencies.

Table 30. Injury criteria for the lower extremities under blunt coronal loading – regulatory

Criterion Nomenclature	Injury Criterion	Agencies
LBr8	Leg flail < 35°	FAA [39]

Criterion Nomenclature	Injury Criterion	Agencies
LBr9	Femur force and bending moment	IIHS [26]

State-of-the-Art Injury Criteria

Table 31 provides a summary of coronal state-of-the-art injury criteria.

Table 31. Injury criteria for the lower extremities under blunt coronal loading – state-of-the-art injury criteria

Criterion Nomenclature	Injury Criterion	Tolerance Limits/Criteria	Comments	Derived from
LBac5	Plantar Foot Load [54]	9.1 kN for 50% risk of any foot-ankle injury (50 years) Other probability levels given in table 2-4 of [54].	• Provides risk curves for 3 Groups of fracture; all foot-ankle, any calcaneus, and any tibia injury	PMHS
LBac6	Knee Injury Criterion [57]	$D_{shearing} = -0.054 * B^2_{bending} - 0.62 * B_{bending} + 25$ for $B_{bending} \geq 9°$ $D_{shearing} = 15$ mm for $B_{bending}$ between 0° and 9°	-	PMHS and FEA

State-of-the-Art Injury Research

None reported.

REFERENCES

[1] Courses.lumenlearning.com. (2017). *Mapping the Body | Boundless Anatomy and Physiology*. [online] Available at: https://courses.lumenlearning.com/boundless-ap/chapter/mapping-the-body/ [Accessed 12 Dec. 2017].

[2] US Code of Federal Regulations, Title 14, Part 25.562. Emergency Landing Dynamic Conditions. Washington, DC: U.S. Government Printing Office, 1988.

[3] US Code of Federal Regulations, Title 49, Part 571.208. Occupant Crash Protection. Washington, DC: US Government Printing Office, 2011.

[4] Uniform Provisions Concerning the Approval of Vehicles with Regard to the Protection of the Occupants in the Event of a Frontal Collision, Regulation No. 94 Rev3. 14 September 2017.

[5] Car Safety Performance Guidebook. New Car Assessment 2014.3. Japan New Car Assessment Program

[6] Moderate Overlap Frontal Crashworthiness Evaluation Guidelines for Rating Injury Measures. Insurance Institute for Highway Safety, September 2014.

[7] Assessment Protocol – Adult Occupant Protection v.7.0.3. European New Car Assessment Programme, November 2015.

[8] US Code of Federal Regulations, Title 14, Part 25.785. Seats, Berths, Safety Belts, and Harnesses. Washington, DC: US Government Printing Office, 2011.

[9] US Code of Federal Regulations, Title 49, Part 571.201. Occupant Protection in Interior Impact. Washington, DC: US Government Printing Office, 2011.

[10] Kleiven, S., “Predictors for traumatic brain injuries evaluated through accident reconstructions”, *Stapp Car Crash Journal* Vol. 51 (2007).

[11] Takhounts E., Hasija V., Ridella S., Rowson S., Duma S., “Kinematic Rotational Brain Injury Criterion (BRIC)” In *Proceedings of the 22nd Enhanced Safety of Vehicles Conference.* Paper, no. 11-0263. 2011.

[12] Laituri T., Henry S., PLine K., Li G., Frankstein M.,Weerappuli P., “New Risk Curves for NHTSA’s Brain Injury Criterion (BrIC): Derivations and Assessments”. *Stapp Car Crash Journal* Vol. 60 (2016): 301-362.

[13] Takhounts E., Craig M., Moorhouse K., McFadden J., Hasija V., “Development of Brain Injury Criteria (BrIC)”, *Stapp Car Crash Journal* Vol. 57 (2013): 243-266.

[14] Kimpara H., Iwamoto M., “Mild Traumatic Brain Injury Predicstors Based on Angular Accelerations During Impacts”, *Annals of Biomedical Engineering* Vol. 40 (2012): 114-126

[15] Raymond D., Van Ee C., Crawford G., Bir C., “Tolerance of the skull to blunt ballistic temporo-parietal impact”, *Journal of Biomechanics* Vol. 42 (2009): 2479-2485

[16] Vorst M., Chan P., Zhang J., Yogonandan N., Pintar F., “A New Biomechanically-Based Criterion for Lateral Skull Fracture”, *Annual Proceedings Associations for the Advancement of Automotive Medicine* Vol. 48 (2004): 181-195

[17] Vorst M., Stuhmiller J., Ho K., Yogonandan N., Pintar F., "Statistically and Biomechanically Based Criterion for Impact-Induced Skull Fracture", *Annual Proceedings Associations for the Advancement of Automotive Medicine* Vol. 47 (2003): 363-381

[18] Rowson S., Duma S., "Brain Injury Prediction: Assessing the Combined Probability of Concussion Using Linear and Rotational Head Acceleration", *Annals of Biomedical Engineering* Vol. 41 (2013): 873-882

[19] Weaver, A.A., Talton, J.W., Barnard, R.T., Schoell, S.L., Swett, K.R., and Stitzel, J.D., "Estimated Injury Risk for Specific Injuries and Body Regions in Frontal Motor Vehicle Crashes", *Traffic injury prevention* 16, no. sup1 (2015): S108-S116.

[20] Zhang L., Yang K., King A., "A Proposed Injury Threshold for Mild Traumatic Brain Injury", *Journal of Biomechanical Engineering* Vol. 126 (2004): 226-236

[21] Deck C., Willinger R., "Improved Head Injury Criteria Based on Head FE Model", *International Journal of Crashworthiness* Vol. 13 (2008): 667-678

[22] Sahoo D., Deck C., Willinger R., "Brain Injury Tolerance Limit Based on Computation of Axonal Strain", *Accident Analysis and Prevention* Vol. 92 (2016): 53-70

[23] Greenwald R., Gwin J., Chu J., Crisco J., "Head Impact Severity Measures for Evaluating Mild Traumatic Brain Injury Risk Exposure", *Neurosurgery* Vol. 62 (2008): 789-798.

[24] Federal Motor Vehicle Safety Standards – Standard No. 214; Side Impact Protection, 49 C.F.R. §571.214 2011.

[25] Uniform Provisions Concerning the Approval of Vehicles with Regard to the Protection of the Occupants in the Event of a Lateral Collision, Regulation No. 95 Rev2. 13 February 2014.

[26] Side Impact Crashworthiness Evaluation Guidelines for Rating Injury Measures (Version III). Insurance Institute for Highway Safety, May 2014

[27] Federal Aviation Administration Special Conditions: Honda Aircraft Company Model HA-420; Single-Place Side-Facing Seat Dynamic Test Requirements. No. 23-263-SC, Washington, DC: Federal Aviation Administration, April 2015.

[28] Van Auken R., Smith T., Zellner J., "Development of a Probabilistic Skull Fracture Model for a 50^{th} Percentile Adult Male Motorcyclist ATD Headform", In *22nd International Technical Conference on Enhanced Safety of Vehicles, Paper*, pp. 11-00035. 2011.

[29] ISO 13232-5: 2005. Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices Fitted to Motorcycles – Part 5: Injury indices and Risk/Benefit Analysis.

[30] Kullgren A., Eriksson L., Bostrom O., Krafft M., "Validation of Neck Injury Criteria Using Reconstructed Real-Life Rear-End Crashes with Recorded Crash Pulses", In *Proc. 18th ESV Conf*, pp. 1-13. 2003.

[31] Bass C., Salzar., R., Lucas S., Rafaels K., Damon A., Crandall J., "Re-evaluating the Neck Injury Index (NII) Using Experimental PMHS Tests" *Traffic Injury Prevention* Vol. 11 (2010): 194-201

[32] Parr J., Miller M., Colombi J., Schubert K., Pellettiere J., "Development of a Side-Impact (Gy) Neck Injury Criterion for Use in Aircraft and Vehicle Safety Evaluation", *IIEE Transactions on Occupational Ergonomics and Human Factors* Vol. 3 (2015): 151-164

[33] Duma, Stefan M., Jeff R. Crandall, Rodney W. Rudd, and Richard W. Kent. "Small female head and neck interaction with a deploying side airbag." *Accident Analysis & Prevention* 35, no. 5 (2003): 811-816.

[34] Meyer F., Bourdet N., Gunzel K., Willinger R., "Development and Validation of a Coupled Head-Neck FEM – Application to Whiplash Injury Criteria Investigation", *International Journal of Crashworthiness* Vol. 18 (2013): 40-63

[35] Viano D., Davidsson J., "Neck Displacements of Volunteers, BioRID P3 and Hybrid III in Rear Impacts: Implications to Whiplash Assessment by a Neck Displacement Criterion (NDC)", *Traffic Injury Prevention* Vol. 3 (2002): 105-116

[36] Viano D., Parenteau C., "Analysis of Head Impacts Causing Neck Compression Injury", *Traffic Injury Prevention* Vol. 9 (2008): 144-152

[37] Munoz D., Mansilla A., Lopez-Valdes F., Martin R., "A Study of Current Neck Injury Criteria Used for Whiplash Analysis. Proposal of a New Criterion Involving Upper and Lower Neck Load Cells", In *Proceedings of the 19th Experimental Safety Vehicles Conference,* pp. 6-9. 2005. Paper number: 05-0313

[38] Heitplatz F., Sferco R., Fay P., Reim J., Kim A., Prasad P., "An Evaluation of Existing and Proposed Injury Criteria with Various Dummies to Determine Their Ability to Predict the Levels of Soft Tissue Neck Injury Seen in Real World Accidents", In *18th International Technical Conference on the Enhanced Safety of Vehicles*. 2003.

[39] Federal Aviation Administration Policy ANM-25-03-R1 - Technical Criteria for Approving Side-Facing Seats. Washington, DC: Federal Aviation Administration, 2012.

[40] Federal Aviation Administration Special Conditions: TIMCO Aerosystems, Boeing Model 777-300ER Series Airplanes; Dynamic Test Requirements for Single-Occupant, Oblique (Side-Facing) Seats with Airbag Devices. No. 25-604-SC, Washington, DC: Federal Aviation Administration, November 2015.

[41] Panjabi M., Ivacic P., Tominaga Y., Wang J., "Invertebral Neck Injury Criterion for Prediction of Multiplanar Cervical Spine Injury Due to Side Impacts", *Traffic Injury Prevention* Vol. 6 (2005): 387-397

[42] Song, E., Lecuyer, E. and Trosseille, X., "Development of injury criteria for frontal impact using a human body FE model", In *Proc. of the 22nd Int. Tech. Conf. on the Enhanced Safety of Vehicles*. 2011.

[43] Kent, R., Patrie, J., Poteau, F., Matsuoka, F. and Mullen, C., "Development of an age-dependent thoracic injury criterion for frontal impact restraint loading", *InProc. of 18th International Technical Conf. on Enhanced Safety of Vehicles*. 2003.

[44] Petitjean, A., Baudrit, P. and Trosseille, X., "Thoracic Injury Criterion for Frontal Crash Applicable to All Restraint Systems", *Stapp Car Crash Journal* Vol.47 (October 2003): 323-348.

[45] Arregui-Dalmases, C., Kerrigan, J.R., Sanchez-Molina, D., Velazquez-Amejide, J. and Crandall, J.R., "A Review of Pelvic Fractures in Adult Pedestrians: Experimental Studies Involving PMHS Used to Determine Injury Criteria for Pedestrian Dummies and Component Test Procedures", *Traffic Injury Prevention* Vol.16 (2016): 62-69.

[46] Salzar, R.S., Bass, C.R., Kent, R., Millington, S., Davis, M., Lucas, S., Rudd, R., Folk, B. and Donnellan, L., "Development of Injury Criteria for Pelvic Fracture in Frontal Crashes", *Traffic Injury Prevention* Vol.7 (2006): 299-305.

[47] Rupp, J.D., Schneider, L.W., "Injuries to the hip joint in frontal motor-vehicle crashes: biomedical and real-world perspectives", *Orthopedics Clinics of North America* Vol.35, no. 4 (2004): 493-504.

[48] US Code of Federal Regulations, Title 14, Part 25 Appendix SFAR 109. Special Federal Aviation Regulation No. 109. Washington, DC: U.S. Government Printing Office, 2009.

[49] Yoganandan, N. and Pintar, F.A., “Deflection, Accelerations, and Forces Corridors for Small Females in Side Impacts”, *Traffic Injury Prevention* Vol. 6 (2005): 379-386.

[50] Mertz, H. and Irwin, A., “Biomechanical and Scaling Bases for Frontal and Side Impact Injury Assessment Reference Values”, *Stapp Car Crash Journal* Vol.47 (October 2003): 155-188.

[51] Pintar, F.A. and Yoganandan, N., “Dynamic Bending Tolerance of the Human Forearm”, *Traffic Injury Prevention* 3, no. 1 (2002): 43-48.

[52] Begeman, P.C. and Paravasthu, N.S., “Proposed Provisional Reference Values for the Humerus for Evaluation of Injury Potential” No. 962416. SAE Technical Paper, 1996.

[53] Begeman, P.C. and Pratima,K., “Bending Strength of the Human Cadaveric Forearm Due to Lateral Loads”, No. 99SC24. SAE Technical Paper, 1999.

[54] Yoganandan, N., Chirvi, S., Pintar, F.A., Uppal, H., Schlick, M., Banerjee, A., Voo, L., Merkle, A. and Kleinberger, M., “Foot-Ankle Fractures and Injury Probability Curves from Post-mortem Human Surrogate Tests”, *Annals of Biomedical Engineering* Vol. 44, (October 2010), 2937-2947.

[55] Smith, B.R., Begeman, P.C., Leland, R., Meehan, R., Levine, R.S., Yang, K.H. and King, A.I., “A Mechanism of Injury to the Forefoot in Car Crashes”, *Traffic Injury Prevention* Vol.6 (2005). 156-169.

[56] Kuppa, S., Wang, J., Haffner, M. and Eppinger, R., “Lower Extremity Injuries and Associated Injury Criteria”, *In 17th ESV Conference*, Paper, no. 457, 2001.

[57] Mo, F., Masson, C., Cesari, D. and Arnoux, P.J., “Coupling Lateral Bending and Shearing Mechanisms to Define Knee Injury Criteria for Pedestrian Safety”, *Traffic Injury Prevention* Vol.14 (2013), 378-386.

[58] Parr, J.C., Millerc, M.E., Pellettiered, J.A., and Erichc, R.A. (2013). Neck Injury Criteria Formulation and Injury Risk Curves for the Ejection Environment: A Pilot Study, Aviation, Space and Environmental Medicine, 84(12), pp. 1240-1248.

[59] Eiband A., Human Tolerance to Rapidly Applied Accelerations: a Summary of the Lit-erature. NASA Memorandum 5-19-59E., NASA Lewis Research Center, Cleveland OH, 1959.

[60] Stech E., Payne P., Dynamic Models of the Human Body, AMRL-TR-66-157, Aero-space Medical Research Laboratory, Wright-Patterson AFB Ohio, 1969.