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The impact of factors and parameters occurring during selected dynamic tests of aircraft seats on the possibility of safe evacuation and loss of consciousness

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Abstract

PURPOSE: The aim of the study was to analyze whether current aircraft seat testing procedures provide sufficient information to determine if passengers will be able to safely and independently evacuate the aircraft after an emergency landing - with a particular focus on the risk of loss of consciousness resulting from head injuries.

METHODS: The study was based on 17 dynamic laboratory tests of economy-class aircraft seats using anthropomorphic test devices (ATDs - Hybrid II). Two test configurations were analyzed: impact against a bulkhead and impact against the seat in the row ahead (row-to-row, R2R). Head Injury Criterion (HIC) values, head accelerations, and impact zones were measured to assess the risk of brain injury and potential loss of consciousness.

RESULTS: Bulkhead-type tests more frequently exceeded the acceptable HIC threshold (>1000), indicating a higher risk of severe neurological injury and loss of consciousness. R2R configurations showed lower risk levels. A particularly significant protective factor was greater seat pitch - HIC values dropped considerably for pitch values >35”. The most frequently impacted head region was the frontal area (91% of cases).

CONCLUSIONS: Although current testing procedures comply with FAA and EASA regulations, they do not fully reflect real clinical risks. It is recommended to supplement the tests with criteria that include rotational accelerations (e.g., BrIC, HIRC), analyse diverse passenger populations (e.g., children and elderly), and revise regulatory standards to include seat pitch as a critical safety parameter.

KEYWORDS: head injury criterion; HIC; loss of consciousness; seat pitch; aviation safety; emergency landing

1. Introduction

Air travel is widely considered one of the safest modes of transportation. However, there are still many aviation accidents, the most common causes of which are pilot error, aircraft technical failures, and adverse weather conditions [5], [13]. Atmospheric disturbances are the cause of most weather-related air accidents, and clear air turbulence (away from convection and mountain waves) is particularly difficult to detect and avoid. Data from around the world indicate that between 1981 and 2020, the number of cases of clear-air turbulence, i.e., turbulence not associated with crossing atmospheric fronts, thick cloud layers, or mountain ranges, increased significantly in five regions: North Africa, East Asia, the Middle East, and over the North Atlantic and North Pacific. Depending on the area, the increase ranged from

60% to 155% [4]. There are many reports emphasizing the importance of the aviation industry's ongoing pursuit of new levels of safety to prevent accidents, injuries, or fatalities [5], [13].

High levels of safety are achieved thanks to strict regulations governing the aviation industry, which are designed not only to prevent accidents, but also to ensure that passengers survive emergency landings with minimal injury. The US Federal Aviation Administration (FAA) has conducted a series of crashworthiness programs that included full-scale aircraft crash tests and dynamic tests of aircraft seats, accident data analysis, and crashworthiness analytical methods. The goal was to link the crash event to the subsequent response of the aircraft/passengers and relevant injury criteria [15], [33]. Aircraft crashworthiness takes into account three key factors: maintaining sufficient living space during a crash, preventing passengers from hitting internal structural elements or being ejected from the aircraft, and mitigating the forces acting on passengers to a level that is tolerable for them [9]. Seats play a key role in mitigating the impact loads transferred from the aircraft to the passenger [7].

One of the critical risks in the event of an emergency landing is the direct consequences of potential injuries and factors limiting the ability to safely leave the aircraft. In this case, we are talking about sudden effects such as loss of consciousness, serious and sudden motor impairments, which ultimately prevent passengers or crew members from efficiently and safely exiting the aircraft fuselage. In transport aviation, the requirements for passenger seats and stations are specified in parallel in CS/FAR 25.785 [22] and 25.562 [23]. The first of these, 25.785 [22], defines functional requirements, including head and body protection when safety systems are used correctly, and refers to general safety criteria under emergency loads. The second (25.562) [23] specifies the requirements for dynamic crash tests, procedures for selecting critical configurations, impulse profiles, rules for evaluating the HIC index, and other injury criteria. The tests used procedures and requirements in accordance with AC 25.562-1B [21].

Traumatic brain injury (TBI) often occurs as a result of mechanical overload during an emergency landing. These injuries are associated with the destruction of the soft tissues of the head. This group includes damage to cerebral vessels, neuron deformation, hypoxia, cerebral tissue edema, or increased intracranial pressure. One of the most severe types of brain injury is diffuse axonal injury (DAI). It occurs primarily as a result of rapid rotational head movements, which stretch, twist, and damage nerve fibers (axons) in the brain's white matter. Unlike focal injuries (such as brain hematomas or contusions), DAI is diffuse, meaning damage occurs in multiple brain areas simultaneously.

Studies show that when the skull collides with an obstacle, there is a sudden increase in pressure at the site of the injury. This is followed by the formation of a so-called suction vacuum between the surface of the brain and the skull [2]. When the head is subjected to linear acceleration, damage usually occurs in the central parts of the head, e.g., in the corpus callosum. However, during angular acceleration, damage to the surface of the brain is most visible, e.g., injuries to the cortex, vascular system, e.g., pons veins. Sudden deceleration of the head causes relative movement of brain structures in relation to the skull. The brain then moves in the direction of the force vector and hits the inside of the skull. However, as a result of sudden acceleration of the head, the brain cannot keep up with the movement of the skull and a relative displacement of the brain in relation to the skull occurs. This mechanism is referred to in the literature as a contrecoup injury. One of the more common complaints that may occur as a result of trauma are disorders of the frontal lobes, which are responsible for executive functions such as problem solving, the ability to shift attention, and control of impulsive behavior through self-observation [11], [16] concentration, short-term memory and learning [12], [18], [34], [35], speed of information processing [30], and speech and language functions [3], [8], [17], [32], [36].

One of the most important indicators used to assess the risk of head injury is the Head Injury Criterion (HIC). This parameter was developed to quantitatively determine the potential degree of brain damage resulting from short-term overloads acting on the human head. HIC is widely used in vehicle crash tests, as well as in the analysis of the effects of accidents in sports, aviation, and even in the safety assessment of protective equipment such as helmets. It is based on measuring the acceleration of the head over time and takes into account both its value and duration. This provides a more comprehensive assessment than maximum linear acceleration alone. The HIC value is calculated based on the recorded acceleration of the head over time (most often in tests using anthropomorphic dummies) according to the formula:

$$HIC = \left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1) \qquad (1)$$

where:

- a(t) – instantaneous acceleration of the head (expressed in units of gravitational acceleration G),
- t1, t2 – time intervals (in seconds) limited to a maximum of 15ms or 36ms, depending on the application.

In practical terms, two versions of HIC are most commonly used: HIC15, calculated within a maximum interval of 15ms, and HIC36, calculated within an interval of up to 36ms or unlimited.

Figure 1 shows the probability of head injury for a given HIC value. The threshold value of HIC =1000 has been adopted as a conventional limit at which there is an approximately 18% probability of serious brain injuries (e.g., concussion, skull fracture) and an approximately 6% risk of life-threatening injuries.

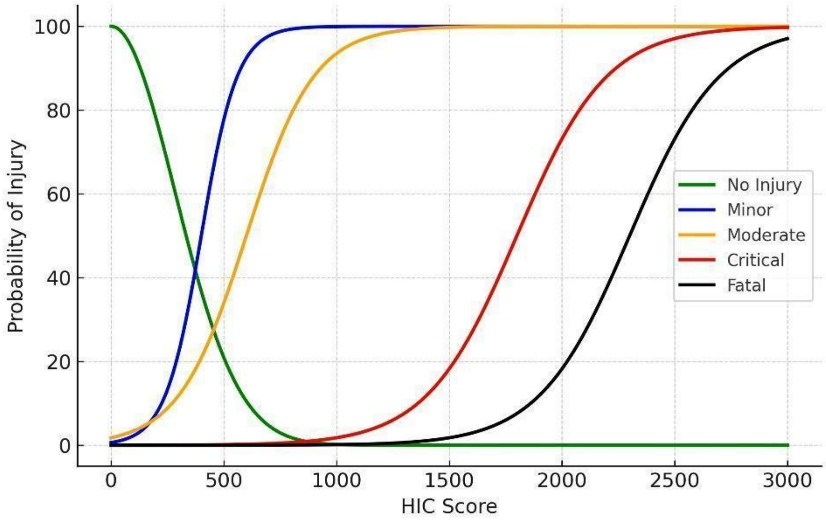

Figure 1. Probability of head injury for a set HIC value, based on [37]

Another important criterion to consider is the Wayne State University Tolerance Curve (WSUTC), which determines the resistance of the human head to dynamic injuries as specified in applicable standards. The curve shows the relationship between the head's tolerance to dynamic contact loads, which arise from a collision with an obstacle, and the value of linear acceleration and duration. Any point above this level indicates life-threatening values. Figure 2 WSUTC suggests that the head can withstand very high acceleration for a very short time, e.g., for a time of 2ms, the permissible acceleration is 400g. Any increase in the duration of the impact at the same acceleration intensity can cause head injury [29], [19].

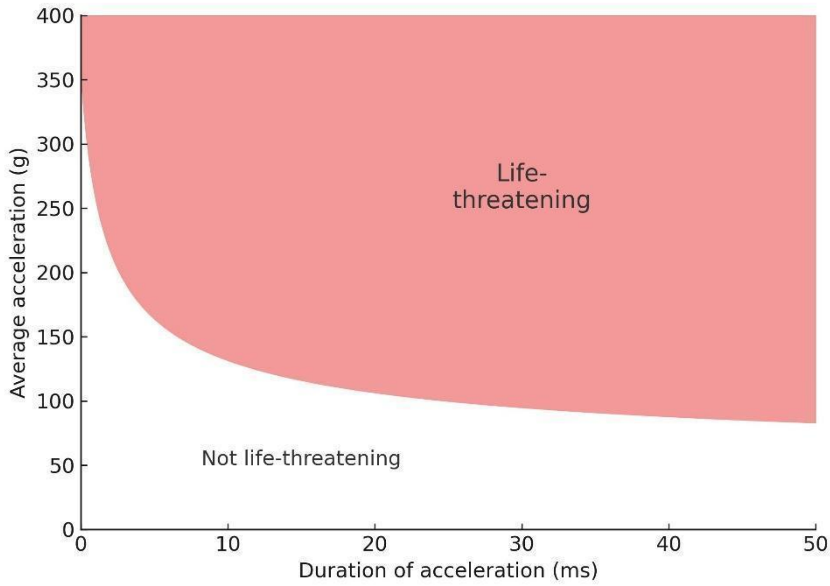

Figure 2. WSUTC curve, based on [19]

Average acceleration values:

- g < 100g Low – low risk of injury,
- 100g-180g Moderate – possible minor injuries,
- 180g-250g High – potentially dangerous,
- >250 g Very high – risk of severe injury.

BrIC (Brain Rotational Injury Criterion)

The BrIC was developed by the National Highway Traffic Safety Administration (NHTSA) as an indicator of the risk of brain injury resulting from rotational head motion. Unlike HIC, which assesses the effect of linear acceleration on the skull, BrIC takes into account angular head velocities, a key factor in the mechanism of diffuse axonal injury (DAI). The BrIC formula is based on the maximum angular velocities (or accelerations) in the X, Y, and Z axes, normalized to their critical values:

$$BrIC = \sqrt{(\frac{\omega_x}{\omega_{cx}})^2 + (\frac{\omega_y}{\omega_{cy}})^2 + (\frac{\omega_z}{\omega_{cz}})^2}$$

where:

- $\omega_x, \omega_y, \omega_z$– maximum angular velocities (or accelerations) of the head along the three principal axes,
- $\omega_{cx}, \omega_{cy}, \omega_{cz}$– empirically determined critical angular velocity values for each axis, representing tolerance thresholds for brain injury.

Head Impact Rotational Criterion (HIRC)

The Head Injury Risk Curve (HIRC), i.e. the head injury risk curve, is used to estimate the probability of a head injury depending on the value of a given biomechanical indicator, most often HIC (Head Injury Criterion) or head acceleration. Therefore, HIRC is a risk function, usually presented as a logistic function:

$$P_{injury} = \frac{1}{1 + e^{-(\alpha+\beta X)}}$$

Where:

- P_{injury} – probability of head injury,
- X – biomechanical variable (e.g., HIC or linear head acceleration [g]),
- α, β – statistically fitted parameters (e.g., using logistic regression),
- e – Euler's number (~2.718).

It is worth emphasizing that there is no specific formula for the HIRC, as the curve has its own α and β parameters and depends on: the population (children/adults), the test type (car, sports), the index (e.g., HIC, BrIC), and the level of injury (AIS2+, AIS3+, AIS4+).

It should be noted that various biomechanical indicators have been developed to more accurately assess the risk of head injuries. Although HIC is a widely used and standardized criterion for assessing head injuries, its limitations have necessitated the development of more complex indicators, such as BrIC (Brain Rotational Injury Criterion), Gadd Severity Index (GSI), and Head Impact Rotational Criterion (HIRC), which better reflect the complex biomechanics of brain injuries. The primary limitation of HIC is that it only considers linear head acceleration, ignoring angular (rotational) accelerations, which play a key role in the development of brain injuries, especially in concussions and diffuse axonal injury (DAI). In reality, it is rotational head movements that cause the greatest deformation and shearing of brain structures. Another limitation is the lack of analysis of the direction of force – the index treats acceleration as a scalar value, meaning that two impacts with identical HIC values but acting from different directions can lead to different traumatic consequences. The HIC also does not account for individual anatomical differences such as age, gender, head size, or tissue elasticity. In practice, this means that the HIC threshold value of 1000 will not apply equally to an adult male, female, or child. Furthermore, this index does not describe the brain's internal reactions because it treats the head as a rigid body. It does not reflect stress distribution, cerebrospinal fluid displacement, or local deformations, which are the direct cause of microscopic neuronal damage. Another significant limitation is the dependence of the HIC on the length of the analyzed time interval (e.g., 15 or 36 ms). The result can vary significantly depending on which pulse segment is selected as the most dangerous. In the case of complex, multiphasic impacts, this can lead to underestimation or overestimation of the actual risk. Furthermore, the HIC correlates well only with severe injuries, such as skull fractures or deep brain damage, and does not accurately describe mild injuries (e.g., concussions) or rotational injuries. All these limitations have meant that HIC, despite its simplicity and versatility, is no longer a sufficient tool in modern head injury research. In response to these shortcomings, more complex indices have been developed. In practice, the most effective strategy is to use different criteria in a complementary manner, depending on the biomechanical scenario and the type of risk being analysed. Table 1 presents the key differences between the mentioned parameters.

Table 1. Characteristics of head injury risk parameters

Criterion	Physical parameters	Main purpose	Main purpose	Benefits	Limitations
HIC	Linear acceleration	Vehicle crash tests	Assessment of injury based on head acceleration as a function of time (up to 15–36 ms)	Wide-ranging, standardized, easy to measure	Does not take rotation into account; depends on the time interval
GSI (Gadd Severity Index)	Linear acceleration	Early biomechanics of injuries	Early indicator, expressed as the integral of acceleration raised to the exponent 2.5 over time	Mathematically simple; historically significant	Less precise than HIC; too general
BrIC (Brain Rotational Injury Criterion)	Angular (rotational) acceleration	Helmet testing, fall analysis	Based on angular acceleration in three axes – better reflects DAI mechanisms and shear injuries	Takes brain rotation into account; more accurate for TBI	More difficult to measure; less widespread Lack of complete standardization
HIRC	Angular (rotational) acceleration	Rotational injuries, sports, biomechanics	Establishes a statistical relationship between rotational kinematic parameters and the probability of brain injury	Models real head movement	Still evolving, context-dependent

Although new parameters for assessing head injuries are constantly being developed, it should be emphasized that HIC remains the most frequently and widely used parameter. However, it should be noted that HIC and GSI are derived directly from WSUTC and are its mathematical extensions. All three are based on the same biomechanical foundations: the relationship between head acceleration and its duration. They were developed based on experimental research on the human brain's tolerance to overload, thus constituting a coherent line of development in understanding the mechanisms of head injury. The differences between these criteria stem primarily from their form, accuracy, and data interpretation. The Wayne State University Tolerance Curve (WSUTC) is empirical in nature, a curve that shows the brain's tolerance limit for acceleration. The Gadd Severity Index (GSI) represents the first mathematical approach to this phenomenon, transforming the WSUTC curve into a numerical index that describes the total effect of acceleration over time. The Head Injury Criterion (HIC), on the other hand, is a refined index that focuses on the most dangerous temporal portion of acceleration, thus providing greater precision in assessment. In terms of accuracy, WSUTC only allows for a qualitative assessment, it indicates whether an injury may occur, but does not determine its severity. GSI enables quantitative analysis of the entire acceleration trajectory, while HIC is more precise because it accounts for acceleration variation over time and identifies the section that poses the greatest risk of brain damage. In practice, WSUTC is used primarily in scientific and laboratory research. GSI was used in early safety tests, while HIC is now the standard in crash testing, in the analysis of head injuries in sports, and in the aviation and automotive industries.

One important safety factor that should also be taken into account is loss of consciousness in an aircraft resulting from high acceleration forces (known as G-forces) that exceed the body's ability to maintain adequate blood flow to the brain. G-LOC is a condition in which a pilot or passenger loses consciousness due to a lack of adequate blood flow (and therefore oxygen) to the brain caused by high G-forces, most often in the vertical axis of the body (known as +Gz overload, from head to toe). Table 2 shows comparison between G-LOC and HIC parameters.

Table 2. Comparison between G-LOC and HIC parameters

Category	G-LOC (G-induced Loss of Consciousness)	HIC (Head Injury Criterion)
Type of phenomenon	Physiological response to sustained acceleration	Biomechanical response to impact acceleration
Mechanism	Blood pooling in lower body causes cerebral hypoxia and loss of consciousness	Rapid linear acceleration causes mechanical stress on skull and brain tissue
Duration of action	Long-term exposure (seconds)	Very short-term exposure (milliseconds)
Typical range / threshold	4.5–6+ G (untrained); up to 9–12 G (trained individuals)	Values of ~700–1000 and above indicate high injury risk
Effect	Temporary vision loss, unconsciousness, followed by spontaneous recovery	Potential skull fracture or traumatic brain injury (TBI)
Reversibility	Usually fully reversible after blood flow returns to the brain	Often irreversible; associated with tissue damage
Domain of application	Aviation, space medicine, high-G training	Automotive safety, sports biomechanics, crash analysis
Type of assessment	Physiological and medical (circulatory and neurological function)	Mechanical and biomechanical (force–time relationship)

Loss of consciousness or even loss of awareness can have various causes: from sudden changes in pressure and hypoxia (oxygen deprivation), through medical factors (e.g., heart rhythm disorders, hypoglycemia), to the stress placed on the body during flight maneuvers (G-LOC – G-force induced Loss of Consciousness). The latter is associated with damage to brain tissue. According to the American Association of Neurological Surgeons [38], traumatic brain injury

(TBI) "is a disruption of normal functioning that can be caused by a blow to the head, concussion, or sudden and violent impact of the head against an obstacle. It also occurs when an object penetrates the skull, entering the brain tissue". Depending on the degree of brain damage, TBI symptoms can be mild, moderate, or severe. While mild cases manifest as a short-term change in mental state or consciousness, severe cases can result in prolonged loss of consciousness, coma, and even death [1], [31], [38]. The relationship between acceleration and loss of consciousness is shown in Table 3.

Table 3. Relationship between acceleration, HIC, and loss of consciousness, based on [6], [14], [20], [25], [28]

Head acc., linear	HIC (approx.)	Possible consequences	Risk of losing consciousness
3–4 G		Onset of blurred vision (“gray field”). Reduced blood supply to the retina	Low
4.5–6 G		Total loss of vision (“black field”). Lack of blood supply to the brain	Low
6–9 G		G-LOC (loss of consciousness) The brain stops receiving oxygen.	Low
50–80 G	300–700	Mild concussion	Low to moderate
80–120 G	700–1000	Moderate brain injury	Moderate to high
>120 G	>1000	Severe brain injury, fractures, GCS <13	Very high
>150 G	>1500	Severe neurological damage, prolonged loss of consciousness	Extreme

Note: the limits are not rigid – they depend on the person, the angle of impact, head rotation, etc.

It should be noted that in civil aviation, overloads rarely exceed 1.5–2G during turbulence or sharp turns. Events causing >3G are extremely rare and considered dangerous. Therefore, loss of consciousness in a passenger aircraft is unlikely to be caused by G-forces, but may be caused by other factors: hypoxia (oxygen deprivation, e.g., during decompression), hypoglycemia, dehydration, neurological or cardiac problems, anxiety, panic attacks, or vasovagal syncope. One of the criteria that influences loss of consciousness is the location of the head impact on aircraft equipment, e.g., the back of the seat in front or the wall. Loss of consciousness most often occurs when the frontal part (frontal lobe), parietal part (parietal lobe), base of the skull, or top of the head (skull vault) is struck. Each of these cases is preceded by a loss of consciousness. In the case of diffuse brain injury/DAI - diffuse axonal injury, often without changes in CT - there is a deep loss of consciousness, often coma.

In passenger seat tests, if the ATD (dummy) head comes into contact with the seat back or another structure inside the cabin, the HIC value must not exceed 1000 (in accordance with standard 25.56) [21], [23], where no preferred HIC measurement time window is specified. In strictly defined case, the FAA allows unlimited HIC >1000, when a passenger comes into contact with an airbag. This situation has been taken into account in the 14 CFR Part 25 regulations concerning the Boeing delegation [27].

In emergency landing situations, especially during sudden deceleration, passengers are exposed to overloads resulting in the risk of their heads coming into contact with cabin elements. Impact with a bulkhead or the structure of the seat in front (row-to-row) can lead to injuries to the skull, brain, and neck structures, which directly affects the ability to evacuate independently, which is crucial in the event of fire or smoke. For this reason, dynamic crash tests are important to determine the head injury criterion (HIC), correlate it with the location of contact and the likelihood of loss of consciousness.

The aim of the study is: *to analyse whether the current testing procedure for aircraft seats provides sufficient information to determine whether passengers will be able to safely and independently exit the aircraft in the event of an emergency landing (taking into account aviation standards and head injury prediction procedures). The analysis is based on a healthy person (without disorders or medical conditions). The test results are conducted in accordance with standards (25.562, 25.785).*

The content of this manuscript is intended to identify the main risk factors and emphasize the importance of safety systems and procedures that aim to minimize the effects of such incidents, along with a definition of our own recommendations.

2. Materials and Methods

The material for the analysis consisted of laboratory results from dynamic seat tests conducted with anthropomorphic test devices (ATDs). Two configurations were examined: bulkhead (bulk), i.e. impact against a fuselage wall structure, and row-to-row (R2R), where two seat rows are positioned in a critical configuration. The test cases were selected based on static and structural analyses. All tests were carried out in a certified dynamic testing laboratory between 2022 and 2025.

A total of 17 tests were selected, performed on the same type of economy-class product. The investigated aircraft seats featured lightweight structures built from aluminium profiles and composite materials:

- Bulkhead tests – 4 tests, 2 × PASS, 2 × FAIL (a total of 8 ATD measurements),
- R2R tests – 13 tests, 12 × PASS, 1 × FAIL (a total of 15 ATD measurements).

A Hybrid II anthropomorphic test device (ATD) representing the 50th percentile adult male (approx. 175cm, 77kg) was used in the tests. The dummy was instrumented with accelerometers and load sensors placed in key body regions, in accordance with the configuration prescribed for aviation testing, in accordance with AC 25.562-1B [21].

In addition, the environmental conditions in the test facility, including temperature and humidity, were monitored and recorded. For the ATD, this is intended to maintain the range recommended by the manufacturer, ensuring that the dummy's materials preserve their proper elastic and damping characteristics. The guidance in AC 25.562-1B [21] specifies that the ATD should be stabilized for at least 4 hours prior to the test under the following conditions:

- temperature 19–26 °C (66–78 °F),
- humidity approx. 10–70%.

To facilitate the identification of the head impact zones, the head was painted with distinct colors marking the chin, nasal, frontal, parietal, and parieto-occipital areas. For the purpose of this study, certified dynamic tests were selected, conducted on the same type of economy-class product, performed within different certification programs. The seats were lightweight structures composed of aluminium profiles and composite materials.

For each configuration (Bulkhead, Row-to-Row), the seat pitch and setback were set in accordance with the assumptions defined in the test plan, and the occupancy layout of the seats by ATDs was reproduced using symbolic notation. For example, *1-0-0* indicates that, when standing behind a triple seat facing the direction of flight, the ATD is positioned only in the left-hand seat (LH). The bulkhead test (Figure 3) replicated the scenario of occupying a seat in the first row, directly in front of a cabin partition or another rigid structural element. Direction of flight is aligned to +X axis.

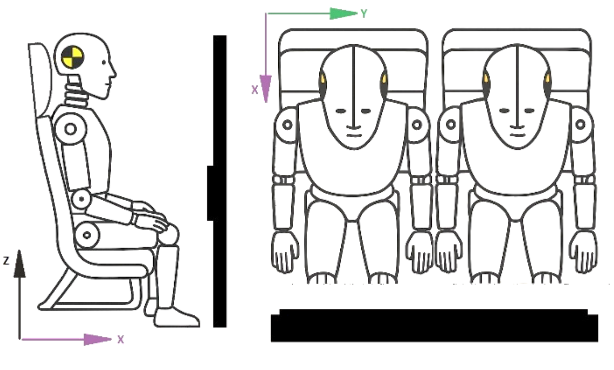

Figure 3. Schematic configuration of a bulkhead test with a Hybrid II ATD; variant 1-1

The Row-to-Row (R2R) test (Figure 4) simulated the passenger's head impact against elements of the seat in the preceding row (e.g., tray table, seatback panel).

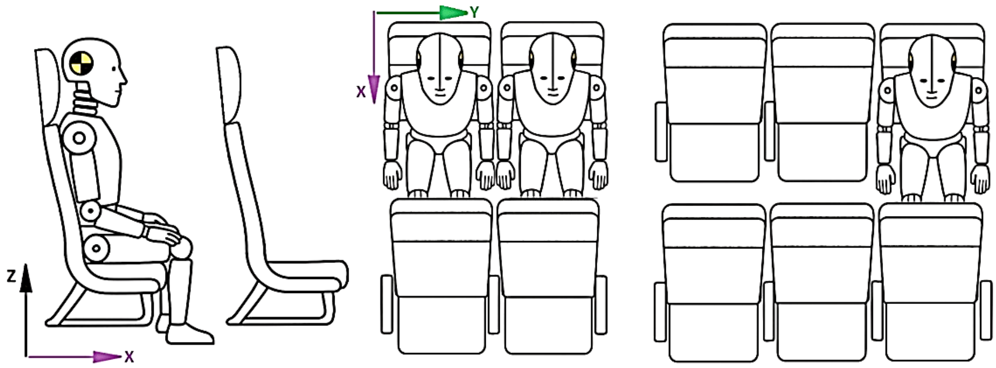

Figure 4. Schematic configuration of an R2R test with a Hybrid II ATD, from left: variant 1-1; 1-0-0

In the trials, an acceleration profile corresponding to the 16G dynamic crash test requirement in the longitudinal (FWD) axis was applied. The duration and shape of the input pulse were monitored to ensure compliance with regulatory guidelines.

During the preparation of the test setup, the Humanetics DPS-1003-HR three-dimensional measurement system was used to define the location of reference points. The system consists of three high-resolution digital cameras, a set of interchangeable measuring probes, and reference markers. This solution enables the automatic determination of point coordinates in a defined reference frame, as well as comparison of the geometry of the object before and after the test to estimate the resulting deformations.

Once the seat platform was mounted on the sled track, a data acquisition system was employed to record signals at a sampling rate of $\geq$10kHz per channel, filtered in accordance with SAE J211/1. Real-time monitoring allowed verification of signal quality before and after each test. In parallel, high-speed video recording 1000fps was conducted from multiple perspectives, synchronized with the sensor data. A total of nine cameras were deployed around the test rig to capture both the global motion of the ATD and the detailed kinematics of the head contact.

Video analysis combined with paint-mark mapping enabled the identification of the specific head regions of the ATD involved in the impact, providing insight into the injury mechanism. The recorded HIC values were automatically compared against regulatory thresholds. During each test, measurements included at least: three-dimensional displacement of head, acceleration and seatbelt tension forces. Based on the acceleration parameters obtained over time, the head injury criterion (HIC) was determined.

3. Results

In emergency landing scenarios, particularly during sudden deceleration, passengers are exposed to loads that may result in head contact with cabin structures. Impact against a bulkhead or the seat structure of the preceding row can lead to skull, brain, and neck injuries, directly affecting the passenger's ability to self-evacuate - a critical factor in fire or smoke conditions. Research conducted in accordance with current certification standards aims to assess whether, and to what extent, such tests reflect the actual condition of the passenger after the event, including their capacity to evacuate the aircraft.

The results of the dynamic aircraft seat tests are presented in Table 4. The table includes data such as configuration (Bulkhead and R2R), with each trial described by the applied scenario, occupancy (distribution of ATDs across seats), outcome (PASS/FAIL), seat pitch/seatback distance, and maximum seatbelt tension. The 'Result' column indicates whether the trial was evaluated as PASS or FAIL by the engineering team, based primarily on the HIC value determined individually for each ATD, along with head acceleration and the resultant delta-time parameter. The 'Impact region' column, based on high-speed video recordings, identifies the specific head zones that came into contact with the obstacle. Six regions were distinguished: (1) frontal, (2) parietal, (3) temporal, (4) occipital, (5) chin and (6) nasal. For bulkhead tests, impact marks were most frequently observed in the upper head area (frontal-parietal), while in R2R tests the contact pattern was more complex, depending on the seat pitch and the geometry of the impacted element.

Table 4. Summary of test parameters and HIC values for bulkhead and R2R tests

No	Type of test	Occupancy	Result	Pitch or seatback [inch]	Position of ATD	HIC	Sleed acc., max. [G]	Head acc resultant, max. [G]	Head acc. resultant, max. - time [ms]	HIC delta time [ms]	Impact region
1	Bulk	1-1	Fail	23	LH - pass	915,3	16,2	196,24	156,15	158,05	frontal-parietal
2					RH - fail	2015		225,91	153,5	163,2	nasal, frontal-parietal
3	Bulk	1-1	Fail	23	LH - pass	795,3	16,2	192,38	156	158,25	frontal-parietal
4					RH -fail	1565		262,84	157,7	158,95	frontal-parietal
5	Bulk	1-1	Pass	23	LH	995,5	16,4	150,47	155,9	176,9	frontal-parietal
6					RH	825,4		167,59	157,45	159,5	frontal-parietal
7	Bulk	1-1	Pass	24	LH	181,1	16,3	89,4	149,4	165,25	no direct impact (slight head contact)
8					RH	450,7		178,87	174,55	161,2	frontal-parietal
9	R2R	1-0-0	Pass	32	LH	623,8	16,9	173,8	175,35	199,25	nasal, chin
10	R2R	1-0-0	Pass	38	LH	665,6	16,5	192,61	179,9	192,85	frontal, nasal, temporal
11	R2R	1-0-0	Pass	42	LH	809	16,9	73,89	149,4	234,5	frontal, parietal, right temporal, occipital during rebound
12	R2R	1-0-0	Pass	41	LH	437,8	16,4	159,6	189,85	176,4	frontal-parietal
13	R2R	1-0-0	Pass	35	LH	761,9	16,6	132,66	133	142,45	frontal, nasal, chin, right parietal and right temporal
14	R2R	1-0-0	Fail	35	LH	1127	16,8	100,91	134,15	149,4	nasal, chin, frontal, left temporal, left side of nasal, right edge of frontal during rebound
15	R2R	1-0-0	Pass	35	LH	476,1	16,9	87,11	130,15	155,75	frontal, nasal, chin
16	R2R	1-0-0	Pass	37	LH	756	16,6	105,05	137,65	170,4	frontal, nasal, chin, right parietal and right temporal
17	R2R	1-0-0	Pass	37	LH	547,7	16,8	142,59	132,6	152,75	frontal, nasal, chin
18	R2R	1-1	Pass	28	LH	503,9	16,8	96,28	117,8	161,8	frontal, nasal, chin
19					RH	395,8		82,26	111,5	157,05	frontal, nasal, chin
20	R2R	1-1	Pass	35	LH	573,8	17,0	74,33	129,35	154,35	frontal, nasal, chin
21					RH	704,5		76,69	128,75	152,8	frontal, nasal, chin (flat), frontal, parietal, temporal, edge of left seatback
22	R2R	1-0-0	Pass	42	LH	611,6	16,7	367,64	197,4	177,5	frontal and parietal during rebound
23	R2R	1-0-0	Pass	41	LH	498,1	17,0	198,24	214,55	166,25	frontal, occipital

Based on the data in the Table 4, a chart was developed showing the distribution of HIC categories (across 4 intervals) by test type and seat pitch or seatback distance (Figure 5).

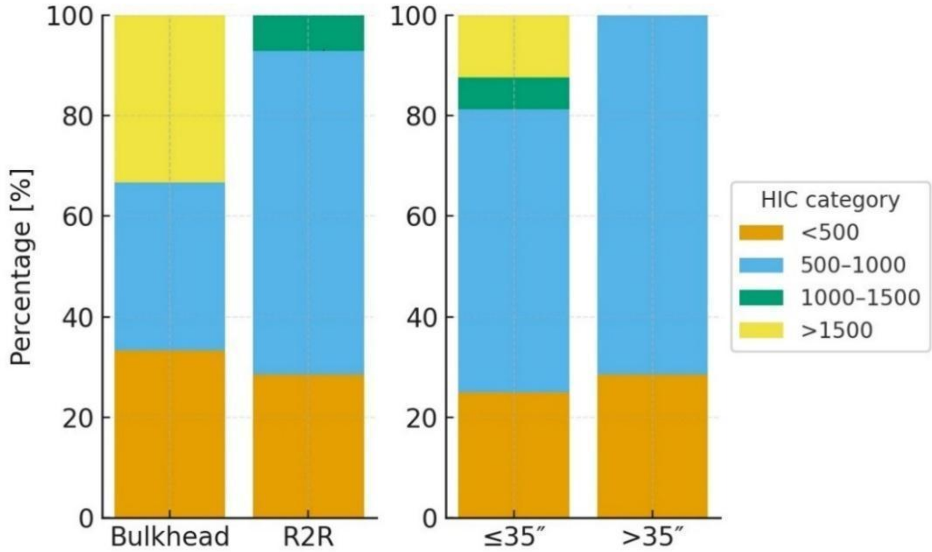

Figure 5. Distribution of HIC categories intervals by test type and seat distance

The plots in Figure 5 show that the R2R test type exhibits a lower share of high-risk categories (HIC >1000) compared to bulkhead tests. For seat pitch values >35″, there were no cases in the highest category (HIC >1500) and a substantial reduction in the proportion of HIC ≥1000. This indicates that increasing the seat pitch beyond 35″ significantly reduces the proportion of cases in the high-risk zone (HIC ≥1000), suggesting a lower probability of loss of consciousness or severe head injury immediately after impact. Risk patterns were further assessed based on video analysis:

- Frontal impacts at smaller pitch (≤35″) generated the highest HIC values and were associated with exceeding the injury tolerance curve.
- The video recordings indicate that at larger pitch (>35″) the point of contact shifted lower or more obliquely, shortening the duration and reducing the amplitude of head acceleration.
- The absence of FAIL outcomes in the lateral and occipital categories in this test series may result from the specifics of the test configuration (ATD positioning).

The definition of the most injury-proneareas (Table 5) showed that the frontal region was most frequently exposed in tests (91.3%), followed by the parietal and nasal regions (52.2%). The analysis was based on the sum of single occurrences across all ATD measurements (23 tests in total), where for each test every head region involved in the impact was counted as one occurrence.

Table 5. Identification of the most critical injury-prone areas - % of impacts

Head region	Chin	Nasal	Frontal	Parietal	Temporal	Occipital
Number of impacts recorded in the specified region across all ATD measurements	10	12	21	13	6	2
% of occurrences for impacts to the given head region	43,5%	52,2%	91,3%	56,5%	26,1%	8,7%

Figure 6 presents the relationship between seat pitch and HIC values as well as head acceleration.

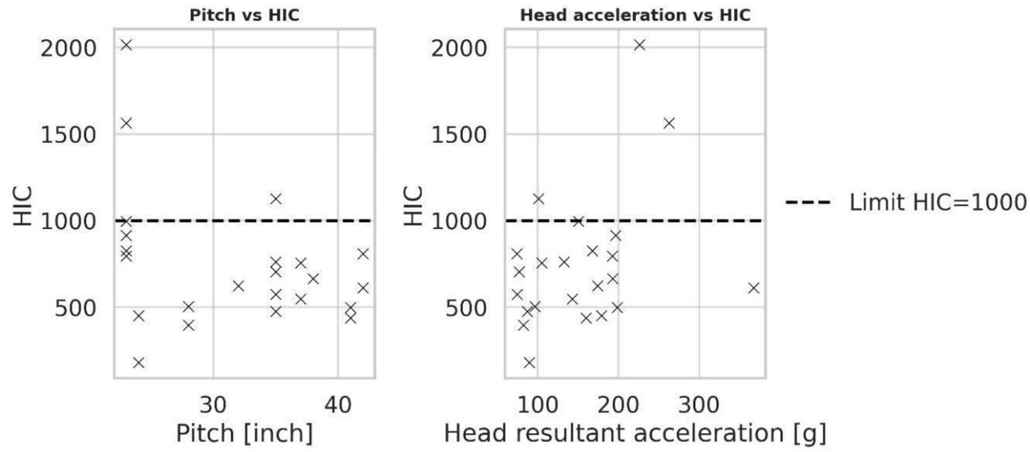

Figure 6. Relation between HIC value and seat pitch and with head acceleration

The data analysis was performed in Python (3.x) using standard statistical and visualization libraries. Spearman's rank correlation was applied due to the characteristics of the dataset and the limited sample size (N = 23). The correlation between HIC values and head acceleration (head_G) was positive, $\rho = 0{,}30$, with weak but suggestive significance ($p = 0{,}16$). Another observed trend indicated that larger seat pitch, particularly ≥35", corresponded to lower HIC values ($\rho = -0{,}37$), although the significance was low ($p = 0{,}08$). It was also evident that head accelerations were distinctly higher in tests resulting in FAIL outcomes and predominated at smaller pitch values (23–24").

Based on criteria related to brain function impairment, it can be concluded that only in test no. 4 (Table 4) was the passenger's probability of loss of consciousness negligible. In the remaining tests, such probability was present to varying degrees. In 11 out of 23 analyzed cases, a low to moderate probability of loss of consciousness was observed. In six cases, this risk was estimated as moderate to high, while in the remaining cases the probability was assessed as very high. For tests not meeting the HIC requirement (values above 1000), the risk of loss of consciousness was estimated as extremely high.

4. Discussion

This study conducted a comprehensive literature review covering head injury mechanisms, injury assessment criteria (with particular emphasis on HIC and alternative parameters), and the clinical consequences of craniocerebral injuries in the context of the ability to self-evacuate from an aircraft. Applicable certification regulations were also considered. The study was based on analysis of results obtained from laboratory tests conducted by a global aircraft seat manufacturer between 2022 and 2025.

The results of dynamic tests on aircraft seats clearly indicate that passenger compartment configuration and seat geometry are key determinants of head injury risk, which can ultimately lead to loss of consciousness and limited ability to self-evacuate from the aircraft cabin. Analyzing the obtained data in light of the literature reveals a number of consistent relationships and significant limitations of currently used safety assessment methods. It is important to note that the main criterion commonly used for injury assessment is the Head Injury Criterion (HIC), a criterion widely used in aviation and automotive applications. Its main advantage is the standardized calculation methodology and the ability to compare values obtained under different test conditions. The results presented in this study confirm that in bulkhead tests, this threshold (HIC >1000) was exceeded more frequently, which corresponded to a significant risk of severe neurological injuries. Similar results were reported in epidemiological studies in road transport, where HIC values >1000 correlated with the occurrence of skull fractures and serious brain injuries [16], [30]. However, it should be emphasized that HIC does not reflect the full complexity of craniocerebral injuries. In particular, it does not account for angular accelerations, which are a major factor in the development of diffuse axonal injury (DAI) [11]. Therefore, the literature increasingly emphasizes the need for parallel use of alternative indices, such as BrIC (Brain Rotational Injury Criterion), HIRC (Head Impact Rotational Criterion), or the classic GSI (Gadd Severity Index), which better describe rotational mechanisms [17], [24]. The results of this study suggest that incorporating rotational criteria into existing test standards could increase their sensitivity in assessing real-world hazards. Test analysis revealed clear differences between the HIC values for the bulkhead and R2R in the test set under consideration. Where the tests were conducted as part of seat certification for several different programmes. In bulkhead tests, the occupant (ATD dummy) experienced significantly higher HIC by direct head contact with the rigid wall.

In the R2R configuration, HIC values were lower on average, and their distribution indicated a lower risk of reaching the >1000 category. These results are consistent with previous studies on aircraft seat safety under impact condition, which demonstrated that the distance to the contact surface (seat pitch) and the nature of the cushioning material significantly reduce the value of achieved head acceleration [10], [13], [15]. Importantly, it was observed that increasing the distance above 35” resulted in a significant decrease in the percentage of cases with HIC ≥1000. This confirms the hypothesis that appropriate passenger compartment geometry can be an effective protective factor. These results should form the basis for consideration of possible adjustments to normative regulations, in which the distance between rows is not currently treated as a critical parameter for occupant neurological safety. Laboratory test results indicating high HIC values in specific configurations should be interpreted in the context of neurophysiological mechanisms leading to loss of consciousness. The literature indicates that injuries to the frontal and parietal lobes can cause impairments in executive functions, working memory, and motor skills [12], [17]. Impacts to the skull base or cranial vault, on the other hand, are associated with the risk of serious neurological disorders, often manifesting as immediate loss of consciousness [2]. The results obtained in this study confirm that the most frequently affected area was the frontal region (91% of all impacts), followed by the nose and crown. This means that traumatic mechanisms leading to loss of consciousness in emergency situations are highly probable and may significantly limit passengers' ability to quickly evacuate. The medical literature emphasizes that even moderate brain injuries (HIC 700–1000) can lead to transient disturbances of consciousness, problems with motor coordination, and slowed reactions [35], [3]. In emergency landing conditions, where time for evacuation is limited (< 90 s), even a momentary impairment in cognitive abilities can have serious consequences for passenger safety. These results suggest that current testing procedures, although compliant with FAA and EASA regulations, do not fully reflect actual clinical risk. In particular, the lack of integration of rotation criteria and the failure to consider differences in passenger age and health constitute a significant limitation of the current standards, and further research is needed to develop a new parameter that will allow for the acquisition of more comprehensive information [22]-[24], [26].

5. Conclusions and recommendations

It should be noted that the HIC parameter has certain interpretation limitations.

HIC only considers linear acceleration, ignoring angular acceleration, which also plays a significant role in brain injuries (e.g., in diffuse axonal injuries such as DAI).

It is not directly relevant for children or the elderly, which is why different standards are used for different populations.

The HIC value depends not only on the maximum G-force but also on its duration – short, sharp pulses can be more dangerous than long, mild G-forces. The mean delta measurement time of the presented tests was 167 ms, which is consistent with the 'unlimited' approach used in aviation. Based on the conducted research and literature review, the following recommendations can be made:

- Consider seat pitch as a safety parameter – results indicate that distances ≥35” significantly reduce HIC values. This should be reflected in regulations regarding minimum row spacing.
- Incorporate rotational criteria (BrIC, HIRC) into test procedures to better represent the mechanisms of diffuse injuries and axonal damage.
- Use additional protective systems – such as seat belts with pretensioners or seatback-mounted airbags, which could significantly reduce the risk of frontoparietal injuries [22]-[24], [26].
- Analyze diverse passenger populations – particularly the elderly and children, for whom the head injury tolerance threshold is significantly lower than in the healthy adult male population.

Future work should focus on expanding the dataset with a larger number of dynamic tests, as this would improve the statistical reliability of the findings and allow for the identification of more subtle patterns. An important area of investigation is the assessment of scenarios not fully addressed by current certification protocols, such as the entrapment of the ATD head in the space between seats, which may generate secondary injury risks and delay evacuation. It would also be valuable to explore whether the observed trends remain consistent across different passenger demographics, including children, elderly individuals, or those with limited mobility. Such extensions, based on broader datasets and more refined statistical approaches, could enhance the understanding of head injury mechanisms and support the ongoing discussion on passenger safety in crash conditions.

Conflict of interests

All authors declare no competing interests.

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