

# INJURY MECHANISMS AND SURVIVAL IN FIGHTER AIRCRAFT EJECTIONS BASED ON A SYSTEMATIC REVIEW

**Muhammad Hilmi Wiratama<sup>1\*</sup>, Indri Hapsari Susilowati<sup>2</sup>,**  
Magister Keselamatan dan Kesehatan Kerja (K3), Universitas Indonesia  
E-mail: [hilmiwiratama0@gmail.com](mailto:hilmiwiratama0@gmail.com)

Received : 05 February 2026

Accepted : 01 April 2026

Revised : 15 February 2026

Published : 09 April 2026

## Abstract

*The ejection seat system in fighter aircraft is a safety technology that plays a crucial role in saving pilots in flight emergencies. However, the high vertical acceleration during the early ejection phase and the propulsion phase exposes pilots to significant axial loads, increasing the risk of spinal cord injury. This systematic review was conducted following PRISMA 2020 guidelines by reviewing literature from Scopus (n = 20) and PubMed (n = 12) databases. After screening and assessing eligibility, 15 studies were included in the qualitative synthesis. The results showed that axial compression of the spine during the early ejection phase was the most common injury mechanism. Vertebral fractures, particularly in the thoracolumbar segment, were the most frequently reported acute injuries. In addition to biomechanical factors, pilot survival is also influenced by operational factors, particularly the timing of the ejection decision and the altitude at which ejection was initiated. Delayed ejection has been reported to be associated with an increased risk of fatality. Thus, injury severity and survival are influenced by the interaction between axial biomechanical loads and operational decisions in emergency situations. These findings demonstrate the importance of an integrated safety approach through the development of ejection system designs, improvements to operational training, and monitoring the occupational health of fighter aircraft crews.*

**Keywords:** *Fighter aircraft ; Ejection Seat ; Spinal compression; Survivability; Axial acceleration; Operational limits*

## INTRODUCTION

Fighter aircraft operations take place in environments that pose a very high level of risk, both aerodynamically and physiologically for the pilot. In flight emergencies, crew safety is a top priority, so various rescue systems have been developed to minimize casualties (Stepień et al., 2017). One of the most important technologies is *the ejection seat*, designed to allow the pilot to quickly exit the aircraft's cockpit when the situation becomes uncontrollable. As technology advances, this system has been proven to increase the pilot's chances of survival in various military aviation incidents. However, the ejection process is not without risk, as the high accelerations that occur during the seat's launch can have serious medical and biomechanical consequences for the pilot's body (Newman, 2013).

Modern (Ata & Yazgan, 2022) *ejection seats operate through a combination of ejection mechanisms that generate high vertical thrust in a very short time. This system is designed to allow the pilot to safely separate from the aircraft, pass through the canopy, and then enter the automatic parachute deployment phase*. In practice, *ejection seat performance* depends not only on propulsion power, but also on the integration of various engineering components, the body's biomechanical response, operational conditions, and human factors. This complexity makes ejection seat design a multidisciplinary challenge. Although system reliability has improved over time, the high acceleration loads during ejection remain a major issue that has not been fully resolved (Epstein et al., 2020).

Numerous studies have shown that the rapid vertical acceleration during the initial ejection phase results in significant axial loading on the pilot's spine. This impact most often manifests as injuries to the thoracolumbar segment. Clinical and operational analyses consistently identify axial compression as the dominant injury mechanism in fighter jet ejection events. Even in well-functioning systems, vertebral fractures are still reported with considerable frequency. This demonstrates the inevitable trade-off between the need for powerful thrust to rescue the pilot and the biomechanical risks the human body must endure during the process (Zeng et al., 2022). Survival after ejection is not solely determined by the mechanical performance of the seat. Operational factors are equally important, particularly the timing of the pilot's decision to eject, the altitude at which the ejection is initiated, and compliance

with recommended operating limits. Numerous accident analyses have shown that delayed ejection is consistently associated with an increased risk of fatality, even when the ejection system performs as designed. These findings emphasize that successful ejection is the result of a complex interaction between humans and technological systems, not simply a matter of hardware reliability (Yang et al., 2022).

Although the literature on fighter jet ejection is extensive, much of the research remains fragmented. Some studies focus on the clinical aspects of injury, while others focus on engineering performance or operational factors separately. This fragmented approach makes it difficult to fully understand how these various factors interact to determine ejection outcomes. To date, a comprehensive synthesis that simultaneously integrates biomechanical, engineering, operational, and human factors perspectives remains relatively limited. Yet, ejection safety is inherently a multidisciplinary, systemic issue that cannot be fully understood from a single perspective.

This limited integration of knowledge highlights the need for more comprehensive studies to support improved military aviation safety. An integrated understanding is crucial not only to reduce the risk of spinal cord injury but also to increase the probability of pilot survival in various emergency scenarios. Furthermore, a robust synthesis of evidence can provide a scientific basis for developing next-generation ejection seat designs, improving operational training, and strengthening occupational health programs for fighter aircraft crews. Therefore, systematic reviews have strategic value from both a technical and human safety perspective.

Based on these considerations, this study aims to systematically review the literature discussing injury mechanisms in fighter jet ejection events and the factors influencing pilot survival. The study also seeks to integrate findings from various clinical, biomechanical, engineering, and operational domains to provide a more comprehensive picture of the determinants of ejection safety in the context of modern military aviation.

## 2. LITERATURE REVIEW

Fighter aircraft operations take place in environments with a very high level of risk, both aerodynamically and physiologically for the pilot. In flight emergencies, crew safety is a top priority, so various rescue systems are continuously being developed to minimize casualties (Stępień et al., 2017). One of the most important technologies is *the ejection seat*, which is designed to allow the pilot to quickly exit the aircraft cockpit when the situation becomes uncontrollable. As technology advances, this system has proven to increase the pilot's chances of survival in various military aviation incidents. However, the ejection process is not without risk, as the high acceleration during seat deployment can have serious medical and biomechanical consequences for the pilot's body (Newman, 2013).

Modern ejection seats operate through a combination of ejection mechanisms that generate high vertical thrust in a very short period of time. This system is designed to allow the pilot to safely separate from the aircraft, pass through the canopy, and then enter the automatic parachute deployment phase (Ata & Yazgan, 2022). In practice, ejection seat performance depends not only on propulsion power but also on the integration of various engineering components, the body's biomechanical response, operational conditions, and human factors. This complexity makes ejection seat design a multidisciplinary challenge. Although system reliability has improved over time, the high acceleration loads during ejection remain a major issue that has not been fully addressed (Epstein et al., 2020). Numerous studies have shown that the rapid vertical acceleration during the initial ejection phase results in significant axial loading on the pilot's spine. This impact most often manifests as injuries to the thoracolumbar segment. Clinical and operational analyses consistently identify axial compression as the dominant injury mechanism in fighter jet ejection events. Even in well-functioning systems, vertebral fractures are still reported at a relatively high frequency. This situation demonstrates the inevitable *trade-off* between the need for powerful thrust to rescue the pilot and the biomechanical risks the human body must endure during the process (Zeng et al., 2022).

Survival after ejection is not solely determined by the mechanical performance of the seat. Operational factors are equally important, particularly the timing of the pilot's decision to eject, the altitude at which the ejection is initiated, and compliance with recommended operating limits. Numerous accident analyses have consistently shown that delayed ejection is associated with an increased risk of fatality, even when the ejection system performs as designed. These findings emphasize that successful ejection is the result of a complex interaction between humans and technological systems, not simply a matter of hardware reliability (Yang et al., 2022).

Although the literature on fighter jet ejection is extensive, much of the research remains fragmented. Some studies focus on the clinical aspects of injury, while others focus on engineering performance or operational factors separately. This fragmented approach makes it difficult to fully understand how these various factors interact to determine ejection *outcomes*. To date, a comprehensive synthesis that simultaneously integrates biomechanical, engineering, operational, and human factors perspectives remains relatively limited. Yet, ejection safety is inherently

a multidisciplinary, systemic issue that cannot be fully understood from a single perspective. This limited integration of knowledge highlights the need for more comprehensive studies to support improved military aviation safety. An integrated understanding is crucial not only to reduce the risk of spinal cord injury but also to increase the probability of pilot survival in various emergency scenarios. Furthermore, a robust synthesis of evidence can provide a scientific basis for developing next-generation ejection seat designs, improving operational training, and strengthening occupational health programs for fighter aircraft crews. Therefore, systematic reviews have strategic value from both a technical and human safety perspective. Based on these considerations, this study aims to systematically review the literature discussing injury mechanisms in fighter jet ejection events and the factors influencing pilot survival. The study also seeks to integrate findings from various clinical, biomechanical, engineering, and operational domains to provide a more comprehensive picture of the determinants of ejection safety in the context of modern military aviation.

### 3. METHOD

#### Study Design

This study employed a systematic literature review approach, structured according to the *Preferred Reporting Items for Systematic Reviews and Meta-Analysis* (PRISMA 2020) guidelines. This approach was chosen to ensure a transparent, structured, and replicable literature search and selection process. All review stages included developing a predetermined search strategy, determining study eligibility criteria, a step-by-step screening process, systematic data extraction, and assessing the methodological quality of each included study. The PRISMA framework aims to enhance the evidence synthesis and enhance its reliability (Page et al., 2021).

#### Search Strategy

A comprehensive literature search was conducted in two major electronic databases, Scopus and PubMed. In Scopus, the search strategy was applied through the title, abstract, and search terms, as follows:

TITLE-ABS-KEY ("ejection seat" AND ("fighter aircraft" OR "military aircraft" OR "combat aircraft"))

AND LIMIT-TO (DOCTYPE, "ar")

AND LIMIT-TO (SRCTYPE, "j")

AND LIMIT-TO (LANGUAGE, "English")

Meanwhile, on PubMed the search strategy used is as follows:

("ejection seat"[Title/Abstract]) AND (fighter OR military OR combat)

Additional filters on PubMed included English language, human subjects, and full-text availability. The final search identified a total of 32 records, consisting of 20 Scopus articles and 12 PubMed articles.

#### Eligibility Criteria

The identified studies were then selected based on pre-determined inclusion and exclusion criteria.

Inclusion criteria include:

- peer-reviewed journal articles;
- English language publications;
- studies involving fighter aircraft or military aviation contexts;
- research that addresses injury mechanisms, survivability, propulsion characteristics, operational factors, or human outcomes related to ejection seat use.

Exclusion criteria include:

- studies of non-ejection related aviation injuries;
- articles in the form of educational commentary or instructional reports;
- publication of policies without injury or survivability analysis;
- non-human simulation studies or purely theoretical studies that are not relevant to ejection biomechanics or safety outcomes

#### Study Selection

The selection process was conducted in stages according to the PRISMA process. Titles and abstracts were first screened to assess relevance to ejection injury mechanisms and survival. Articles meeting the initial criteria were then reviewed in full text to ensure compliance with the inclusion criteria.

One identified duplicate record was removed before the screening stage. After the selection process was completed, 15 studies met all criteria and were included in the qualitative synthesis. The study selection flow is presented in the PRISMA diagram in Figure 1.

## Data Extraction

Data was extracted using a structured matrix that included:

- Author and publication year
- Aircraft context
- Study design
- Sampling or modeling framework
- Primary injury mechanism
- Determinants of survival ability
- Main findings
- Implications for aviation safety

Extraction was performed to enable cross-domain synthesis across clinical, engineering, and operational evidence.

## Quality Assessment

Given the heterogeneity of methodological designs among the included studies, this study used a multi-tool assessment approach. Retrospective clinical and observational studies were assessed using the Newcastle–Ottawa Scale (NOS) (Gualdi-Russo & Zaccagni, 2026). Systematic reviews included in the sample were evaluated using AMSTAR 2. (Lunny et al., 2025) Case reports were assessed using the Joanna Briggs Institute (JBI) checklist.

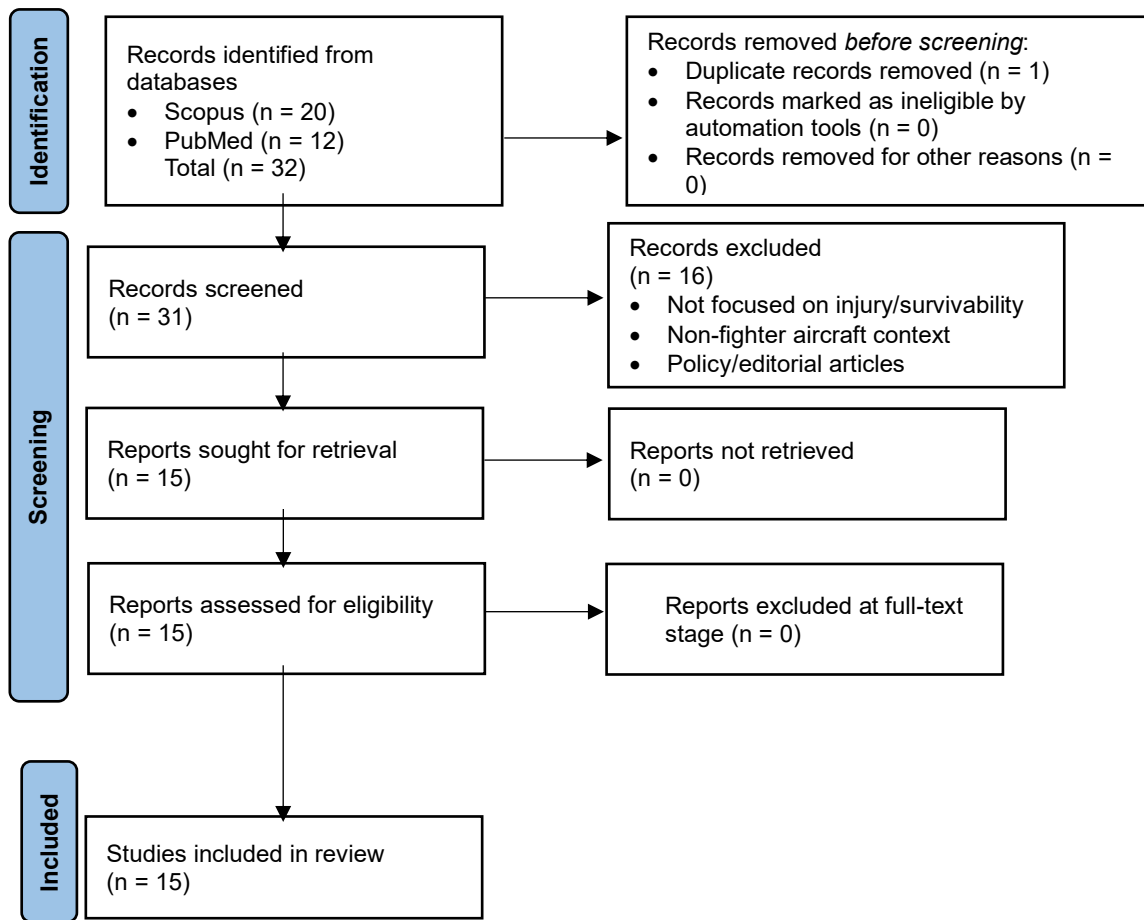
Meanwhile, engineering modeling and reliability studies were evaluated using structured methodological criteria that emphasize model transparency, clarity of assumptions, and rigor of the validation process. This approach was used to ensure that the quality of evidence was assessed proportionally according to the characteristics of each study design.

## 4. RESULTS AND DISCUSSION

### a. Study Selection

A total of 32 records were identified through database searches (Scopus = 20; PubMed = 12). After removing one duplicate, 31 records were screened based on title and abstract. After screening, 16 records were excluded. Fifteen full-text articles were assessed for eligibility, and 15 studies were included in the qualitative synthesis. The study selection process is summarized in the PRISMA flow diagram (Figure 1).

Figure 1. PRISMA 2020 flowchart depicting the study selection process across the stages of database identification, screening, eligibility assessment, and inclusion.



**b. Study Characteristics**

The 15 included studies were published between 1994 and 2025 and represent diverse methodological approaches. Study designs included retrospective clinical analyses, with the majority of studies conducted in the context of military fighter aircraft. Data were derived from operational accident reports, hospital-based injury evaluations, simulation-based biomechanical experiments, and engineering system reliability modeling. Sample sizes varied, from single trauma case reports to analyses of accident databases spanning multiple decades. The included studies demonstrated a variety of methodological approaches, including observational clinical studies, operational accident analyses, engineering modeling, biomechanical experiments, and literature reviews. The distribution of study designs across the included literature is shown in Figure 1. Figure 1. Distribution of study designs in the included literature (n = 15). The majority of studies used observational clinical designs and operational accident analyses, while experimental biomechanical studies and systematic reviews appeared in a more limited number.

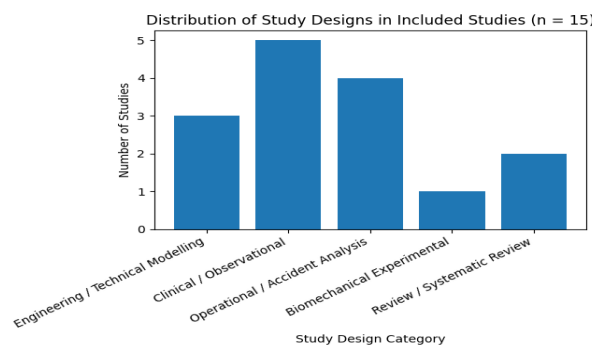


Table 1 summarizes the characteristics of the included studies. Across the included literature, findings are organized into four thematic domains:

# INJURY MECHANISMS AND SURVIVAL IN FIGHTER AIRCRAFT EJECTIONS BASED ON A SYSTEMATIC REVIEW

Muhammad Hilmi Wiratama and Indri Hapsari Susilowati

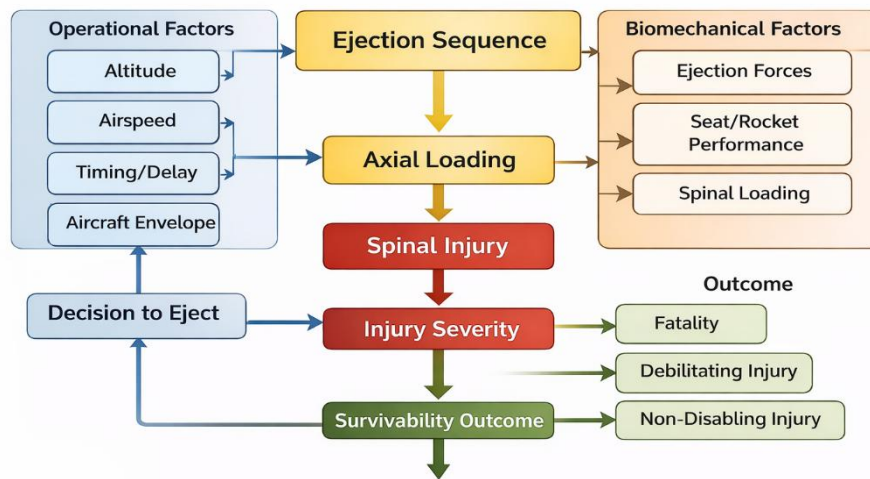
1. Spinal cord injury mechanisms and biomechanics
2. Survival and operational factors
3. Engineering reliability and propulsion characteristics
4. Human factors and long-term job impacts

Table 1. Characteristics and Main Focus of Included Studies (n = 15)

No	Writer	Aircraft Context	Study Design	Sample/Model	Main Focus
1	(BASTUG et al., 2025)	Fighter	Engineering modeling	MATLAB trajectory simulation	Ejection trajectory and clearance analysis
2	(Parate, 2025)	Military aircraft	Root cause analysis	Gas generator system	Propulsion failure mechanism
3	(Tandon et al., 2023)	Fighter	Reliability modeling	Life support system model	System reliability integration
4	(Sommer et al., 2023)	Fighter aircraft (Germany)	Retrospective clinical cohort	103 crew members	Spinal cord injury incidents
5	(Parate, 2022)	Military fighter aircraft	Technical review	Literature study	Rocket propulsion mechanics
6	(Yang et al., 2022)	Fighter pilot	Cross-sectional study	66 pilot	Prevalence of low back pain
7	(Osborne & Cook, 1997)	Military fighter aircraft	Retrospective injury analysis	18 crew members	Spinal fracture
8	(Lowry et al., 1994)	US military aircraft	Death review	57 fatal cases	Survival pattern
9	(Epstein et al., 2020)	Israeli Air Force	Systematic review	30 studies	Injury pattern synthesis
10	(Newman, 2013)	High performance aircraft	Operational review	Low altitude ejection case	Limits of survival
11	(Daudin et al., 2013)	Fighter	Retrospective medico-psychological study	Post-ejection pilot	Psychological response
12	(Damon et al., 2010)	Military aircraft	Experimental biomechanical studies	PMHS Model	Spinal kinematics
13	(Lewis, 2006)	Royal Air Force	Retrospective operational analysis	232 cases	Rocket thrust and injury
14	(Zivkovic et al., 2024)	Jet fighter aircraft	Case report	Single case	Polytrauma in low altitude ejection
15	(Miles, 2015)	US Air Force	Accident database review	20 years of data	Impact of delayed ejection

Based on the study characteristics in Table 1, the analyzed literature demonstrates a relationship between flight operational factors, ejection system characteristics, and the pilot's biomechanical response during ejection. The interaction of these factors contributes to the spinal cord injury mechanism and the survival outcomes of flight crew members. To conceptually illustrate this relationship, a synthetic framework was developed that summarizes the relationship between operational factors, biomechanical exposure during ejection, and the resulting injury outcomes.

Figure 2. Conceptual framework of injury mechanisms and survival outcomes in fighter jet ejections based on a synthesis of the included literature.



**c. Mechanism of Spinal Cord Injury during the Ejection Process**

As shown in the conceptual framework in Figure 2, spinal injuries are the most consistently reported finding in the literature regarding fighter jet ejections. Retrospective clinical analyses and operational injury studies indicate that axial compression in the early phase of ejection seat deployment is the primary mechanism of injury, particularly when ejection occurs at certain flight speed and altitude combinations. (Osborne & Cook, 1997). The thoracolumbar vertebrae have been reported to be the most frequently affected in various studies (Sommer et al., 2023). Examples of spinal injury patterns reported in the literature are shown in Figure 3, which depicts vertebral compression fractures in the thoracolumbar vertebrae following a fighter jet ejection event.

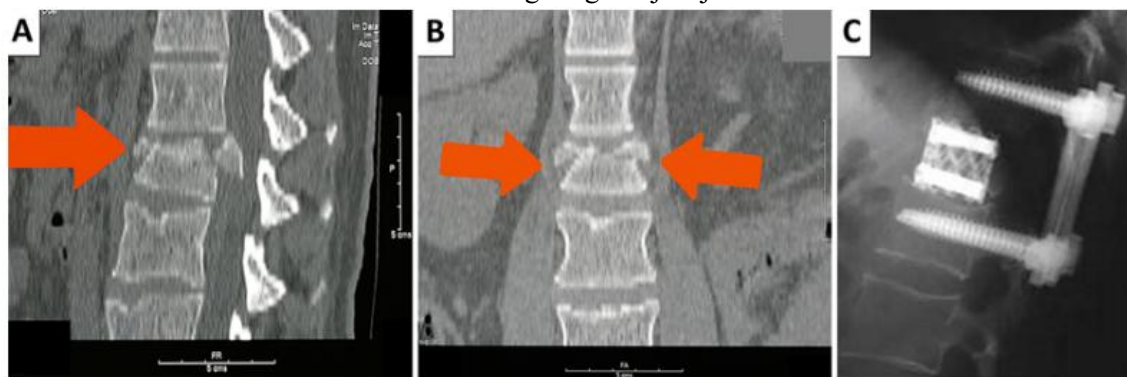


Figure 3. Example of vertebral compression fracture in the thoracolumbar segment after ejection. fighter aircraft. (A–B) CT scan shows L1 incomplete burst fracture in Panavia Tornado crew after ejection. (C) Postoperative radiograph after

Spinal decompression and stabilization using posterior instruments. Adapted from Sommer et al., 2023.

The figure depicts a compression fracture pattern often associated with exposure to high axial acceleration during the early phase of ejection, which causes increased compressive loading on the thoracolumbar segments of the spine. These clinical findings are reinforced by experimental biomechanical studies using *post-mortem human surrogates* (PMHS). Laboratory studies demonstrate vertebral displacement and a significant increase in compressive loads when the body is exposed to high vertical accelerations (Damon et al., 2010). The consistency between experimental evidence and clinical observations strengthens the suspicion of a causal relationship between rapid upward acceleration and spinal compression fractures in pilots during ejection.

Furthermore, operational cohort analysis indicates that injury severity is influenced not only by physiological factors, but also by the thrust characteristics and propulsion parameters of the ejection seat (Lewis, 2006). Variations in the thrust profile can alter the magnitude of the axial load transmitted to the pilot's body during the launch phase. Overall, the existing literature consistently supports that axial compression in the early phase of seat propulsion is the dominant biomechanical mechanism underlying spinal cord injury in fighter aircraft ejection events.

#### d. Survival Ability and Operational Factors

As shown in the conceptual framework in Figure 2, the ejection survival of a fighter jet is significantly influenced by the operational context at the time the ejection decision is made. Numerous studies have shown that the probability of survival is highly dependent on the altitude at initiation, adherence to *the operational procedure/envelope*, and the timing of the pilot's decision to eject (Newman, 2013). These factors are often the primary determinants of safety outcomes, even when the ejection system is mechanically operating as designed. Several accident analyses have consistently shown that delayed ejection is associated with an increased risk of fatality (Miles, 2015). This underscores the limited time margin in aviation emergencies, so even small delays can significantly impact the chances of survival. Furthermore, studies of fatal incidents have identified that ejections occurring outside recommended operational limits and parachute failure are frequent contributing factors to crew deaths (Lowry et al., 1994). On the other hand, case report-based evidence suggests that survival can still occur when ejections occur outside certified operational limits, although they are generally accompanied by severe injuries or polytrauma (Zivkovic et al., 2024). These findings suggest that ejection success is not solely determined by the mechanical reliability of the system, but also by the interaction between technological performance and the quality of pilot decision-making under highly time-constrained operational conditions.

#### e. Engineering Reliability and System Performance

Several engineering studies have shown that ejection success is determined not only by the pilot's physiological tolerance, but also by the integrity of the system and the reliability of the ejection seat propulsion. An engineering perspective shows that a small failure in a critical component can significantly reduce the chance of survival, even if the pilot's condition is within biomechanical tolerances (Parate, 2022). Root cause analysis identifies several potential failure points in the propulsion system, including material fatigue, combustion instability, and propellant cartridge failure. These factors can disrupt the designed thrust profile and ultimately degrade ejection performance. (Parate, 2025). In addition, reliability modeling studies using hierarchical structures and *fault tree analysis* indicate that life support system integration is a critical component influencing the success of an escape event (Tandon et al., 2023).

Trajectory modeling research also provides insight into how mechanical parameters such as launch velocity, ejection angle, and seat mass affect post-ejection clearance and operational limits related to ejection risk. (BASTUG et al., 2025) While these studies did not directly measure injury *outcomes* in humans, the findings provide an important mechanistic basis for understanding the window of survivability. Further engineering considerations highlight the dual nature of rocket-assisted propulsion systems. On the one hand, high thrust is required to ensure safe separation from the aircraft. However, on the other hand, increased thrust also increases the axial acceleration loads transmitted to the pilot's body (Parate, 2025). This interplay suggests that propulsion optimization must always be considered in conjunction with human biomechanical tolerance limits.

#### f. Human Factors and Long-Term Job Impacts

Beyond acute injuries and mechanical performance aspects, a number of studies have also highlighted the broader occupational and psychological consequences of ejection exposure in fighter pilots. A human factors perspective suggests that the impact of ejection does not stop at the initial rescue phase, but can persist in the form of musculoskeletal disorders and long-term psychological adjustment. Cross-sectional studies in fighter pilots have identified a prevalence of chronic low back pain related to accumulated spinal loading over service and repeated

exposure to high-performance seating environments (Abdulwahab, 2021). While these complaints do not necessarily stem from a single ejection event, such chronic exposure has the potential to decrease the baseline spinal tolerance before pilots experience acute high-G accelerations. This can increase susceptibility to injury when an ejection does occur. In addition to the physical aspects, medical-psychological evaluations indicate that ejection events are often followed by acute stress responses and adaptive challenges in the post-event phase (Daudin et al., 2013). These psychological reactions have the potential to impact pilots' operational readiness in the medium to long term. Therefore, the concept of survivability should not be understood solely as immediate physical survival after ejection, but should also encompass functional recovery and psychological readiness. These findings support the importance of a more comprehensive occupational health approach, integrating musculoskeletal monitoring with ongoing psychological evaluation in fighter aircrew.

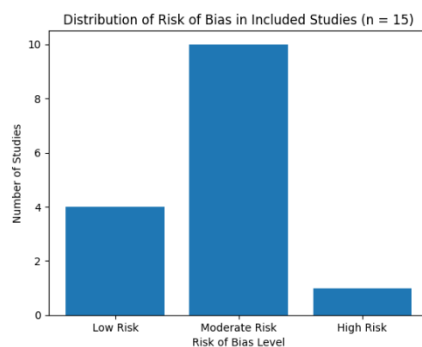
**g. Quality Assessment and Risk of Bias**

Methodological assessment indicated that the quality of the included studies was generally moderate . Retrospective clinical and operational database studies were primarily categorized as having a moderate risk of bias due to historical heterogeneity and reporting variability. The included systematic reviews demonstrated a relatively low risk of bias based on the AMSTAR-2 criteria . Experimental biomechanical investigations were methodologically rigorous within laboratory constraints but limited by cadaveric modeling conditions (Damon et al., 2010). Engineering modeling studies had strengths in computational methodology but generally relied on assumption-based parameters with limited empirical validation . Despite the heterogeneity in study design and methodological constraints, the convergence of findings across clinical, operational, biomechanical, and engineering domains strengthened the internal consistency of the synthesized evidence. Overall, four studies were categorized as having a low risk of bias, ten studies as having a moderate risk of bias, and one study as having a high risk of bias. The distribution of risk of bias levels across the included studies is shown in Figure 4.

Figure 4. Distribution of risk of bias levels in included studies (n = 15). Most studies were categorized as having a moderate risk of bias, with several studies having a low risk of bias and one study having a high risk of bias.

A summary of the results of the methodological quality assessment and the level of risk of bias for each included study is presented in detail in Table 2.

Table 2. Assessment of Quality and Risk of Bias of Included Studies



# INJURY MECHANISMS AND SURVIVAL IN FIGHTER AIRCRAFT EJECTIONS BASED ON A SYSTEMATIC REVIEW

Muhammad Hilmi Wiratama and Indri Hapsari Susilowati

No	Writer	Year	Type of Study	Assessment Tools	Risk of Bias	Main Limitations
1	Bastug et al.	2025	Engineering modeling	Engineering checklist	Low	Assumption-based trajectory parameters; limited field validation
2	Parate	2025	Root cause analysis	Engineering checklist	Currently	Limited external validation; context-specific failure cases
3	Tandon et al.	2023	Reliability modeling	<i>Fault tree</i> /Markov validation criteria	Low	Model-based assumptions; limited empirical confirmation
4	Sommer et al.	2023	Retrospective clinical cohort	NOS	Currently	Heterogeneity of data period (1975–2021); retrospective reporting
5	Parate	2022	Technical review	Narrative review assessment	Currently	No empirical testing; potential publication bias
6	Abdulwahab et al.	2021	Cross-sectional study	NOS	Currently	Self-administered questionnaire-based data; limited generalizability
7	Osborne & Cook	1997	Retrospective injury analysis	NOS	Currently	Small sample size; limited consistency of injury classification
8	Lowry et al.	1994	Death review	NOS	Currently	Limitations of historical databases; potential for misclassification
9	Epstein et al.	2020	Systematic review	AMSTAR 2	Low	Heterogeneity of injury definitions between primary studies
10	Newman	2013	Operational review	NOS	Currently	Operational limit parameter control is limited, so analysis relies primarily on case report summaries.
11	Daudin et al.	2013	Retrospective medical-psychological study	NOS	Currently	Retrospective assessment bias; population-specific context
12	Damon et al.	2010	Experimental biomechanical studies	Laboratory validation criteria	Low	Limitations of the cadaveric model (PMHS) compared to living responses
13	Lewis	2006	Retrospective operational analysis	NOS	Currently	Operational variability; incomplete parameter reporting
14	Zivkovic et al.	2024	Case report	JBI	Tall	Single case; cannot be generalized
15	Miles	2015	Accident database review	NOS	Currently	Potential reporting bias; depends on quality of documentation

## DISCUSSION

### Key Findings

This systematic review demonstrates that spinal compression injuries remain the most frequently reported acute consequence following fighter jet ejection events. The following discussion is organized around the conceptual framework of injury mechanisms and survival outcomes presented in Figure 2. Across clinical and operational

studies, high vertical accelerations in the early launch phase have been consistently associated with vertebral fracture patterns, particularly in the thoracolumbar segment. This consistency of findings reinforces the belief that axial compression is the predominant injury mechanism in high-velocity ejection events. However, the results of this study also show that survival cannot be explained solely from a biomechanical perspective. Pilot survival is influenced by a combination of interrelated factors. On the one hand, sufficient propulsion is necessary for the pilot to safely separate from the aircraft *body*. On the other hand, excessive propulsion actually increases the axial load on the spine. This situation demonstrates an inevitable *trade-off between the aircraft's clearance requirements and the human body's tolerance limits*.

In addition to technical factors, operational aspects also proved to be crucial. Ejection altitude, adherence to *the operational envelope*, and especially the timing of pilot decisions played a significant role in determining outcomes. The available evidence shows that delayed ejection is consistently associated with an increased risk of fatality, even when the ejection system is functioning properly. This confirms that ejection success is a result of the interaction between humans and the system, not simply a matter of device reliability. The review's key findings emphasize that ejection safety must be understood as a multidimensional issue. Efforts to improve survivability go beyond engineering design improvements; they also require strengthening operational training and ongoing monitoring of flight crew health.

## Integration of Biomechanical and Engineering Determinants

One important finding from the included studies is the dual role of the propulsion system in the ejection process. While rocket-assisted thrust is necessary to ensure the pilot can separate quickly and safely from the aircraft, the resulting high vertical acceleration also creates compressive forces along the pilot's spinal axis (Parate, 2025). (Damon et al., 2010) This explains why a system designed for rescue still carries the risk of biomechanical injury. This situation demonstrates the inherent trade-off between engineering requirements and the human body's tolerance limits. Too low a thrust risks failing to provide adequate clearance from the aircraft, while too high a thrust actually increases axial loads and the potential for spinal injuries. Operational analysis also shows that variations in thrust parameters can affect the severity of injuries to ejection pilots, further emphasizing the need for balanced propulsion calibration (Lewis, 2006).

The congruence between clinically reported fracture patterns and kinematic findings from experimental studies further supports the belief that axial compression is the dominant injury pathway (Osborne & Cook, 1997). While engineering modeling studies do not directly measure injury outcomes in humans, they nonetheless provide important mechanistic insights. Parameters such as launch velocity, ejection angle, and mass distribution have been shown to play a role in determining clearance limits and post-ejection safety margins (BASTUG et al., 2025). The integration of biomechanical and engineering evidence in this review emphasizes the importance of balanced ejection system optimization. An approach that focuses too much on increasing thrust without considering human tolerance limits could potentially shift the risk from separation failure to serious pilot injury.

## Survivability as an Operational Phenomenon

Beyond biomechanical exposure, post-ejection survival is also significantly influenced by operational factors. Literature findings indicate that the success of an ejection system depends not only on mechanical performance but also on the quality of pilot decision-making in time-sensitive emergency situations. Even when the hardware is functioning properly, a delay in the ejection decision can significantly reduce the probability of survival. (Miles, 2015). Time margins in aviation emergencies are often very narrow, requiring pilots to make decisions under conditions of high cognitive stress. Numerous accident analyses have shown that ejection scenarios at low altitudes or outside *the operational envelope* are repeatedly associated with fatal outcomes. (Lowry et al., 1994); (Newman, 2013). This condition indicates that compliance with operational limits remains an important protective factor in the ejection process.

These findings demonstrate that survivability cannot be understood solely as a technical parameter. Ejection success is the result of the interaction between the human and the system. In practice, timely decision-making under high cognitive load is a key determinant of successful ejection. Interestingly, several extreme case reports indicate that survival is still possible even when ejection is performed outside certified operational limits, often accompanied by severe injuries or polytrauma (Zivkovic et al., 2024). This underscores that technical success does not always equate to optimal clinical outcomes. Therefore, survivability should be understood as a combined product of mechanical performance, biomechanical tolerance, and operational timeliness.

## Job and Long-Term Implications

Although acute spinal cord injury is the most prominent finding immediately after ejection, long-term occupational exposure also plays a role in shaping pilots' initial tolerance. Cross-sectional evidence suggests that accumulated spinal loading and prolonged exposure to high-performance seating environments are associated with an increased incidence of chronic low back pain in fighter pilots (Abdulwahab, 2021b). This suggests that injury susceptibility is not determined solely by a single ejection event, but also by the musculoskeletal load accumulated over the course of service.

In addition to the physical aspects, the psychological dimension also emerged as an important component that often receives less attention. Medical-psychological evaluations indicate that ejection events can trigger an acute stress response and pose adaptive challenges in the post-event phase (Daudin et al., 2013). These impacts have the potential to impact pilots' operational readiness in the medium to long term, even if they physically survive the ejection event. These findings emphasize that the concept of survivability should not be limited to immediate survival after ejection. A more comprehensive assessment needs to include the pilot's functional recovery and mental readiness after the event. From a safety perspective, an approach that combines regular musculoskeletal monitoring with structured psychological follow-up has the potential to complement the currently dominant engineering-based safety strategy.

## Methodological Considerations

The studies included in this review exhibited a significant degree of methodological heterogeneity, encompassing retrospective clinical cohorts, biomechanical experiments, reliability modeling, and systematic reviews. This diversity of approaches provides a richer, multidisciplinary perspective in understanding ejection safety. However, at the same time, the variety of designs and sample sizes limits the possibility of direct quantitative aggregation (Page et al., 2021).

Most available clinical studies are retrospective and rely on historical reporting systems. This opens the door to documentation bias, incomplete data, and variability in injury classification (Lewis, 2006). Engineering modeling studies, on the other hand, generally demonstrate good methodological rigor but rely on assumption-based parameters and have limited real-world validation (BASTUG et al., 2025). Despite these limitations, findings from across clinical, operational, biomechanical, and engineering domains demonstrate relatively consistent patterns. This thematic convergence across approaches strengthens the overall reliability of the synthesis and emphasizes that understanding ejection safety requires a multidisciplinary perspective.

## Implications for Aviation Safety Practices

The integrated findings of this review support a multidimensional safety framework for fighter aircraft ejection systems. First, propulsion optimization must balance aircraft clearance requirements with biomechanical tolerance thresholds. Second, reliability-focused gas generator maintenance and life support integration remain critical. Third, operational training should emphasize awareness of operational limits and timely decision-making under high-stress conditions. Finally, structured occupational health monitoring can reduce cumulative musculoskeletal and psychological burden.

## Future Research Directions

Future investigations should aim to integrate biomechanical modeling with real-world injury datasets to refine spinal tolerance thresholds under variable thrust profiles. A prospective multicenter injury registry could improve the consistency of injury classification. Furthermore, research exploring cognitive decision thresholds in time-critical ejection scenarios could improve operational survivability modeling.

## CONCLUSION

Fighter aircraft ejection systems remain a crucial life-saving intervention in aviation emergencies. However, the high vertical accelerations required to ensure safe separation from the aircraft inevitably result in significant compression loads on the pilot's spinal axis. The synthesis of clinical, biomechanical, and operational evidence in this review indicates that axial compression in the early phase of launch is the dominant injury mechanism in ejection events. The findings also indicate that survival probability is not determined by a single factor. Ejection *outcome* is the result of a complex interaction between propulsion system performance, human biomechanical tolerance limits, adherence to *the operational envelope/procedure*, and the timeliness of pilot decision-making. Therefore, improving ejection safety requires a multidimensional approach that integrates ejection system design optimization, maintaining

technical reliability, strengthening operational training based on rapid decision-making, and continuous monitoring of pilot occupational health.

## REFERENCES

- Abdulwahab, S. S. (2021). Prevalence of Low Back Pain among Military Fast Jet Pilots. *Aerospace Medicine and Human Performance*, 92(5), 378–384.
- Ata, N., & Yazgan, E. (2022). Analysis of the pilots' decisions to eject in F-16 fighter aircraft accidents in Turkey. *International Journal of Sustainable Aviation*, 8(1), 91. <https://doi.org/10.1504/ijsa.2022.120610>
- BASTUG, E., SERIN, N., & ELALDI, F. (2025). Trajectory analysis and flight modeling of combat aircrafts ejection seats. *Chinese Journal of Aeronautics*, 38(2), 103267. <https://doi.org/10.1016/j.cja.2024.09.043>
- Damon, A. M., Lessley, D. J., Salzar, R. S., Bass, C. R., Shen, F. H., Paskoff, G. R., & Shender, B. S. (2010). Kinematic response of the spine during simulated aircraft ejections. *Aviation Space and Environmental Medicine*, 81(5), 453–459. <https://doi.org/10.3357/ASEM.2688.2010>
- Daudin, M., Renard, M. D., Louzon, V., Chollet, S., & Colas, M. D. (2013). Ejection in hostile environments: Medico-psychological aspects for the fighter pilot. *Aviation Space and Environmental Medicine*, 84(8), 856–858. <https://doi.org/10.3357/ASEM.3596.2013>
- Epstein, D., Markovitz, E., Nakdimon, I., Guinzburg, A., Aviram, E., Gordon, B., Shapira, S., Sharon, S., Steinfeld, Y., Miller, A., & Lipsky, A. M. (2020). Injuries associated with the use of ejection seats: a systematic review, meta-analysis and the experience of the Israeli Air Force, 1990-2019. *Injury*, 51(7), 1489–1496. <https://doi.org/10.1016/j.injury.2020.04.048>
- Gualdi-Russo, E., & Zaccagni, L. (2026). The Newcastle–Ottawa Scale for Assessing the Quality of Studies in Systematic Reviews. *Publications*, 14(1), 4. <https://doi.org/10.3390/publications14010004>
- Lewis, M. E. (2006). Survivability and injuries from use of rocket-assisted ejection seats: Analysis of 232 cases. *Aviation Space and Environmental Medicine*, 77(9), 936–943.
- Lowry, M., Mellen, P., & Weedn, V. (1994). Ejection Seat Aircraft Fatalities in the United States Military, 1966 to 1990. *Journal of Forensic Sciences*, 39(5), 1153–1160. <https://doi.org/10.1520/jfs13699j>
- Lunny, C., Jain, N., Nazari, T., Kosaner-Kließ, M., Santos, L., Goodman, I., Osman, A. A. M., Berrone, S., Dadam, M. N., Brenna, C. T. A., Hussein, H., Dahdal, G., Cespedes, D. A., Ferri, N., Kanji, S., Chi, Y., Pieper, D., Shea, B., Parker, A., ... Tricco, A. C. (2025). Exploring the methodological quality and risk of bias in 200 systematic reviews: A comparative study of ROBIS and AMSTAR-2 tools. *Research Synthesis Methods*, 17, 63–92. <https://doi.org/10.1017/rsm.2025.10032>
- Miles, J. E. (2015). Factors associated with delayed ejection in mishaps between 1993 and 2013. *Aerospace Medicine and Human Performance*, 86(9), 774–781. <https://doi.org/10.3357/AMHP.4057.2015>
- Newman, D. G. (2013). Survival outcomes in low-level ejections from high performance aircraft. *Aviation Space and Environmental Medicine*, 84(10), 1061–1065. <https://doi.org/10.3357/ASEM.3626.2013>
- Osborne, R. G., & Cook, A. A. (1997). Vertebral fracture after aircraft ejection during Operation Desert Storm. *Aviation Space and Environmental Medicine*, 68(4), 337–341.
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Journal of Clinical Epidemiology*, 134, 178–189. <https://doi.org/10.1016/j.jclinepi.2021.03.001>
- Parate, B. A. (2022). Science And Technology of Aircraft Seat Ejection: Advanced Concepts. *Cogent Engineering*, 9(1). <https://doi.org/10.1080/23311916.2022.2034267>
- Parate, B. A. (2025). Root Cause Analysis for a Gas Generator and Ejection Seat System for Aircraft Applications. *Central European Journal of Energetic Materials*, 22(2), 166–179. <https://doi.org/10.22211/cejem/205988>
- Sommer, F., Gadradj, P. S., & Pippig, T. (2023). Spinal injuries after ejection seat evacuation in fighter aircraft of the German Armed Forces between 1975 and 2021. *Journal of Neurosurgery: Spine*, 38(2), 271–278. <https://doi.org/10.3171/2022.8.SPINE22644>
- Stępień, S., Szajnar, S., & Jaształ, M. (2017). Problems of military aircraft crew's safety in condition of enemy counteraction. *Eksploatacja i Niezawodność – Maintenance and Reliability*, 19(3), 441–446.

## INJURY MECHANISMS AND SURVIVAL IN FIGHTER AIRCRAFT EJECTIONS BASED ON A *SYSTEMATIC REVIEW*

Muhammad Hilmi Wiratama and Indri Hapsari Susilowati

---

- Tandon, A., Verma, V. B., & Chaturvedi, S. K. (2023). Hierarchical Reliability Modelling and Analysis of Life Support System of Fighter Aircraft. *International Journal of Mathematical, Engineering and Management Sciences*, 8(4), 595–611. <https://doi.org/10.33889/IJMEMS.2023.8.4.034>
- Yang, Y., Liu, S., Ling, M., & Ye, C. (2022). Prevalence and Potential Risk Factors for Occupational Low Back Pain Among Male Military Pilots: A Study Based on Questionnaire and Physical Function Assessment. *Frontiers in Public Health*, 9(January), 1–10. <https://doi.org/10.3389/fpubh.2021.744601>
- Zeng, J., Liu, X. P., Yi, J. C., Lu, X., Liu, D. D., Jiang, Y. Q., Liu, Y. B., & Tian, J. Q. (2022). Analysis of two naval pilots' ejection injuries: Two case reports. *World Journal of Clinical Cases*, 10(24), 8667–8672. <https://doi.org/10.12998/wjcc.v10.i24.8667>
- Zivkovic, M. M., Inman, B. L., Figlewicz, M. R., Burchett, J. A., & Nowadly, C. D. (2024). Polytrauma in a Jet Pilot After Low-Altitude Ejection Without Parachute Deployment. *Aerospace Medicine and Human Performance*, 95(11), 862–866. <https://doi.org/10.3357/AMHP.6412.2024>