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ORIGINAL ARTICLE

PHYSICAL INJURIES SUSTAINED DURING EJECTION IN THE POLISH AIR FORCE BETWEEN 1951 AND 2025

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Introduction: Ejection is the last resort for saving the lives of an aircraft crew in an emergency. The aim of this study was to conduct a retrospective analysis of ejection incidents in the Polish Air Force between 1951 and 2025, with a particular focus on the effectiveness of the procedure and the physical injuries sustained by pilots.

Methods: The analysis included documentation from the Air Accident Investigation Commission, aeromedical records, operational data, and, where available, information from hospital records and post-ejection interviews. The evaluation covered the ejection outcome, the type of aircraft and ejection seat, the altitude and speed at the time of the incident, the location and severity of injuries, the role of human and technical factors, and the aircraft's continued airworthiness.

Results: A total of 281 ejections were recorded from 255 aircraft, including 177 from subsonic aircraft and 104 from supersonic aircraft. 210 pilots survived, while 71 died. Of the survivors, 44 were uninjured, 40 sustained minor injuries, and 126 sustained serious injuries. Spinal injuries were the most common; 262 vertebral fractures were documented, most frequently involving L-5, S-1, C-5, and Th-8. The highest number of serious injuries and deaths was associated with the KK-1 and KK-2 seats, and the highest fatality rate was linked to ejection at altitudes below 150 meters.

Conclusions: Ejecting effectively saves lives, but it carries a high risk of serious injury, especially to the spine. The results indicate a need to modernize rescue systems, train decision-making thresholds, and establish standardized diagnostic and rehabilitati on procedures following ejection.

Keywords: high-speed jet aircraft, ejection, injuries, vertebral fracture

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INTRODUCTION

Ejection – that is, the emergency exit from an aircraft using an ejection seat—is one of the riskiest procedures a person can undergo in military aviation. Although modern ejection seat technology has reached a high level of sophistication, the risk of serious injury or death remains a real possibility, especially in extreme situations such as high G-forces, low altitude, or system failure.

Over the past 70 years, hundreds of ejection seat models have been implemented (including the Martin-Baker [14], Zvezda [4], and ACES II/ACES 5 [3,5]), yet despite their effectiveness, the number of serious injuries and fatalities remains alarming.

Catapulting is an extreme biomechanical process. Within 0.2–0.4 seconds, the pilot experiences:

- linear and angular accelerations of 12–20 G,
- passing through cabin aerodynamic turbulence (known as "windblast"),
- contact with parts of the cockpit (often during acceleration and body movement),
- compressive stress on the spine (particularly in the cervical and lumbar regions),
- the risk of the parachute failing to open properly (which could result in death or multiple organ injuries),
- contact with the ground, water, or an obstacle with high kinetic energy.

Injuries resulting from ejection are therefore complex in nature, meaning they affect the musculoskeletal, neurological, vascular, and psychological systems.

Since the 1950s, until 2025, according to available data [6], there have been over 14,000 ejections worldwide, of which:

- approximately 82% of cases resulted in survival without permanent disability,
- approximately 9% of cases resulted in serious injuries (including spinal, skull, and limb fractures, as well as paralysis),
- approximately 2.5–3% resulted in immediate death or death due to complications,

The remaining cases are incomplete, undocumented, or classified as "near-misses."

The fatality rate in ejection incidents has decreased significantly in recent series and reviews; however, it remains dependent on altitude, speed, flight phase, and the type of ejection seat [6,9,21]. Research into the injuries sustained by military pilots during ejection is crucial for several reasons:

- they improve the design of ejection seats (e.g., Martin-Baker Mk 18 [14], ACES 5 [3]),
- they support the development of pilot training (simulators, emergency procedures),
- they enable the development of medical protocols in aviation and field medicine,
- they serve as the basis for risk assessment in combat and test missions.

This publication presents the results of an analysis of all ejection incidents that occurred between 1951 and 2025, including both those with positive outcomes and those in which the pilots were killed. The research presented in this paper aimed to determine:

1) the types and locations of serious injuries and the frequency of fatalities related to ejection in the Polish Air Force between 1951 and 2025;
2) the epidemiological profile of ejection incidents, taking into account the type of ejection seat, aircraft type, ejection altitude and speed, and the role of human and technical factors;
3) operational and biomechanical factors potentially associated with the risk of injury, in particular seat type, height, speed, body position, and the phase of the event;
4) the clinical and surgical consequences of ejection, including the type and severity of injuries, loss of consciousness, medical decisions, and the possibility of returning to flight duty;
5) areas of systemic, technological, training, and medical measures that can reduce the risk of severe consequences of ejection and improve the response following such an incident.

METHODOLOGY

The study was a retrospective, observational epidemiological and clinical study. The analysis covered all available cases of military pilots ejecting from their aircraft in the Polish Air Force between 1951 and 2025. The source material included medical records, accident and operational documentation, previous studies on failed ejection seat deployments in the Polish Air Force [11,12], data on the aircraft type and ejection seat used, as well as information regarding the course of the incident, health consequences, and the pilots' continued fitness for flight following completion of treatment and rehabilitation.

The study included cases for which data were available that allowed for the identification of at least the basic variables analyzed in the study, i.e., the outcome of the ejection, the type and location of injuries, and the circumstances of the incident. Where possible, the analysis was supplemented with data from hospital records and information obtained from interviews with pilots following their ejection. On this basis, the

clinical picture of the consequences of ejection was reconstructed, including the occurrence of loss of consciousness, spinal injuries, head injuries, and injuries to the limbs and trunk, as well as subsequent medical and vocational decisions.

The variables analyzed included, in particular: ejection seat type, aircraft type, ejection altitude and speed, type and location of injuries, severity of injuries, the role of human and technical factors in the cause of the incident, as well as the decision regarding continued fitness to fly. Injuries were classified as: no injuries, minor injuries, serious injuries, and fatal injuries. In addition, the distribution of fractures in individual vertebrae and the relationship between the location of the injuries and continued airworthiness were analyzed.

Statistical Analysis

The analysis was conducted using descriptive and comparative statistical methods. For qualitative variables, frequencies and percentages are presented. The Pearson chi-square test was used to analyze the relationships between selected qualitative variables. The level of statistical significance was assumed to be $p < 0.05$.

RESULTS

Table 1 lists all the fractures of specific vertebrae described in the medical records, categorized by the type of ejection seat installed on the aircraft from which the ejection occurred.

The analysis of spinal fractures identified a total of 262 fractures. Most frequently, they involved the L-5 (n = 37) and S-1 (n = 34) segments, followed by C-5 and TH-8 (21 each). The highest number of fractures was observed among pilots ejected from KK-1 and KK-2 seats, which also corresponded to the highest number of ejections performed using these seat types.

Tab. 1. Fractures of individual vertebrae depending on the type of ejection seat used.

Vertebra	Type of ejection seat											Total
	KK-1	KK-2	SK-1	KM-1	KM-1M	KS-2	KS-3	KS-4	K-36	Mk-11	SK	
C-3	1				1							2
C-4	2				3						1	6
C-5	6	3		4	4			1	2		1	21
C-6	5	5		4	1			1	2			18
C-7	1	4		2	1				1			9
TH-1												
TH-2												
TH-3												
TH-4	3			1	1			1			1	7
TH-5	1			1	2			1			1	6
TH-6	4	3			1			3			2	13
TH-7	2	2	1	3				2				10
TH-8	10	1	2	6				1			1	21
TH-9	7	2	1	5				1			1	17
TH-10	4	3						2			1	10
TH-11	4	2		2	2			2	1			13
TH-12	3	2	2	3	2			2				14
L-1	2	1	1	3	1			1				10
L-2			1	1	2							4
L-3					2				1			3
L-4	2	3			2				1			8
L-5	14	9		3	8			1	2			37
S-1	13	8		3	7			1	2			34
S-2												
Total	84	48	8	41	40	0	0	20	12	0	9	262
Number of ejections	63	40	8	26	25		1	11	8	3	25	210

Tab. 2. The type of injuries sustained and their location.

Injury type	Location of injuries				
	Head	Spine	Upper limbs	Torso	Lower limbs
Minor	0	19	12	9	0
Major	10	98	9	5	4

Location and severity of injuries

Based on their location, physical injuries resulting from the ejection process have been classified as follows:

a) Axial and compressive injuries of the spine:
– vertebral body fractures (most commonly L1–L3), in PAF (L5, S1, Th8),
– post-traumatic disc disorders,
– spinal cord injuries – which are particularly dangerous in the presence of undiagnosed spinal stenosis.

b) traumatic brain injuries:
– injuries resulting from a collision with the cab or guard,
– damage to the labyrinth and cranial nerves,
– post-traumatic neurological and mental disorders (including PTSD and post-traumatic epilepsy) [10].

c) limb injuries:
– multiple fractures resulting from incorrect leg positioning at the moment of firing,
– knee injuries (hyperextension, ligament tears),
– amputations in extreme cases resulting from impact with parts of the cockpit.

d) chest and abdominal injuries:
– fractures of the ribs and sternum from the thoracic spine,
– damage to internal organs (liver, spleen),
– pneumothorax caused by a strong windblast.

The types of injuries sustained are shown in Table 2.

The most common site of injury was the spine: 19 minor injuries and 98 severe injuries were reported. Ten severe injuries were found on the head, 12 minor and 9 severe injuries on the upper limbs, 9 minor and 5 severe injuries on the torso, and 4 severe injuries on the lower limbs. These results indicate that spinal injuries were the most common type of injury resulting from ejection.

The pilot's age and the severity of the injuries

The composition of the study group according to injury severity is illustrated in Fig. 1. An analysis of hospitalization records and interviews revealed that 189 pilots reported losing consciousness during the ejection process.

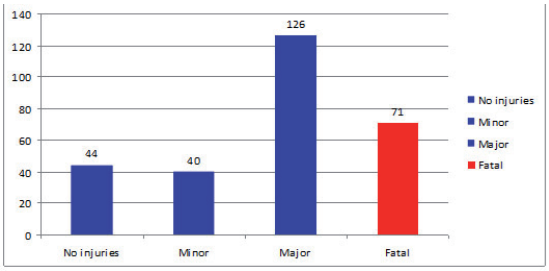


Fig.1. The composition of the study group by severity of injury.

Between 1951 and 2025, 281 pilots ejected from their aircraft while serving in the PAF. Across the entire study group, there were 44 cases with no injuries (15.7%), 40 cases of minor injuries (14.2%), 126 cases of severe injuries (44.8%), and 71 deaths (25.3%).

Fig. 2 shows the age distribution of pilots who ejected, including both successful ejections and those that resulted in the pilot's death. A detailed description of the nature of injuries in each age group is as follows:

Age ≤30
– increased flexibility of the soft tissues and spine,
– a lower risk of compression fractures of the vertebrae,
– greater metabolic resilience to stress,
– However, there is a higher incidence of upper limb and facial injuries due to the incomplete development of protective reflexes.

Age 31–45
– optimal balance between resilience and operational maturity,
– statistically the lowest mortality rate and the best conversion rates,
– Most common injuries: shoulders, lower back, pelvis.

Age >46
– significant increase in the risk of osteoporosis-related fractures (especially L1–L3), prolonged neurological recovery time,
– increased risk of arrhythmia in cases of cardiac contusion.

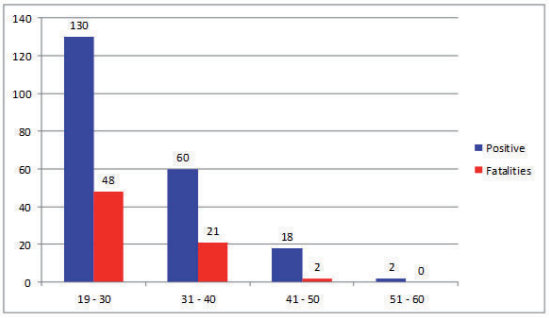


Fig. 2. Age of the pilots at the time of ejection.

Fig. 3 shows the distribution of injuries sustained by pilots in each age group. The largest group consisted of pilots aged 19-30 years,. Severe injuries were the most common in all age groups analyzed.

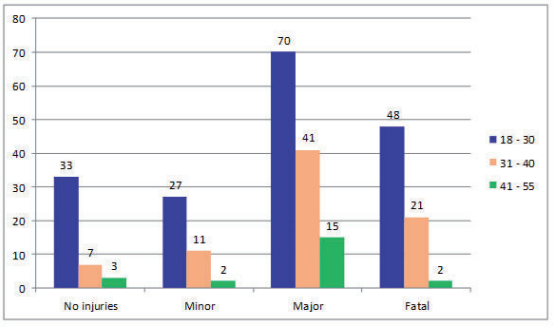


Fig. 3. Types of injuries by age group.

Aircraft type and ejection seat

When reviewing all ejection incidents in the Polish Air Force, it is worth noting the types of aircraft involved in the ejections and the injuries sustained by the pilots. From the graph in Fig. 4, we can see that more ejection seats were deployed from subsonic aircraft than from supersonic ones. The largest group consisted of pilots with serious injuries.

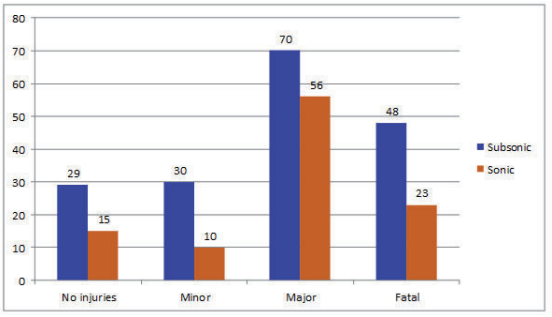


Fig. 4. The extent of injuries varies depending on the type of aircraft.

Table 3 shows the distribution of injuries sustained by Polish military pilots who, over a period of 75 years, ejected from their aircraft using ejection seats. The table below shows just how dangerous the first KK-1 and KK-2 ejection seats were.

The highest number of ejection incidents was recorded for the KK-1 (n = 92) and KK-2 (n = 51) seats. These groups also had the highest number of serious injuries (36 and 21, respectively) and deaths (29 and 11). In later models, the numbers were lower, but serious injuries remained the most common in the KM-1, KM-1M, and KS-4 aircraft as well.

Speed and altitude during ejection

The speed and altitude of the aircraft at the time of ejection are critical factors in determining the injuries pilots may sustain. The types of injuries based on ejection height are shown in Table 4.

The height of the ejection was clearly linked to the severity of the consequences. At altitudes below 150 meters, 40 deaths were recorded in 48 cases, indicating the highest risk of death in this zone. Above 1,000 meters, severe injuries were the most common, but the death rate was significantly lower.

Tab. 3. The type of injury depends on the type of ejection seat.

Ejection seat	Number of injuries				
	No injuries	Minor	Major	Fatal	Total
KK-1	12	15	36	29	92
KK-2	9	10	21	11	51
SK-1	2	3	3	9	17
KM-1	3	2	21	5	31
KM-1M	5	2	18	4	29
KS-3	0	0	1	0	1
KS-4	1	1	9	2	13
SK	6	6	13	7	32
K-36DM	4	0	4	2	10
MK-10	0	0	0	2	2
MK-11	2	1	0	0	3
Total	44	40	126	71	281

The type of injuries, depending on the flight speed at which the ejection occurred, is shown in Table 5.

In the speed analysis, the highest number of ejections was recorded in the 251–400 km/h range (n = 93) and the 401–550 km/h range (n = 81). The highest number of serious injuries was recorded in the 401–550 km/h range (n = 49), while the highest number of fatalities was recorded in the 251–400 km/h range (n = 28).

Circumstances of the incident

An important issue to note is the role of human error in aviation accidents resulting in the pilot ejecting. Table 6 presents this data. The analysis shows that in 162 cases (57.7%), the ejection was caused by human error, while in 119 cases (42.3%), it was caused by a technical failure. The human factor played a greater role in all categories of outcomes, particularly in the group of fatalities, where it accounted for 46 of 71 cases (64.8%).

Another important issue is the decision every pilot must make after ejecting. The rehabilitation period is coming to an end, and a decision must be made regarding the future [31]. Decisions regarding continued airworthiness following ejection and recovery are presented in Table 7.

Of the 44 pilots who ejected without injury and were able to return to flying without any restrictions within six months, 36 decided to return to flying jet aircraft. Eight pilots who had to wait more than 12 months due to a vertebral fracture never returned to flying high-speed jets. The decision regarding medical unfitness was based on unstable fractures that required surgical treatment; these pilots were permitted to fly training aircraft used for the initial cadet course, with the exception of aircraft equipped with ejection seats.

The second group of pilots, who had sustained minor injuries, made the following decisions. Eighteen pilots returned to flying their previous aircraft after completing rehabilitation. Decisions were made to change the training profiles

Tab. 4. The type of injury depends on the height of the launch.

Altitude [m]	Number of injuries				
	No injuries	Minor	Major	Fatal	Total
2001 - >	8	17	33	4	62
1001 - 2000	13	7	33	0	53
501 - 1000	9	6	29	3	47
301 - 500	7	4	13	8	32
151 - 300	5	6	12	15	38
< - 150	2	0	6	40	48
0	0	0	0	1	1
Total	44	40	126	71	281

Tab. 5. The type of injury depends on the speed at which the ejection occurred.

Speed [km/h]	Number of injuries				
	No injuries	Minor	Major	Fatal	Total
700 - >	5	4	11	5	25
551 - 700	12	7	25	11	55
401 - 550	8	10	49	14	81
251 - 400	14	16	35	28	93
< - 250	5	3	6	13	27
Total	44	40	126	71	281

Tab. 6. The role of human and technical factors in ejection incidents.

Factor type	Number of injuries								
	No injuries	%*	Minor	%*	Major	%*	Fatal	%*	Total
Human	26/59%	16	22/55%	14	68/54%	42	46/64.8%	28	162/58%
Technical	18/41%	15	18/45%	15	58/46%	49	25/35%	21	119/42%
Total	44/100%	16	40/100%	14	126/100%	45	71/100%	25	281/100

* within factor type

Tab. 7. Decisions regarding continued airworthiness following ejection and recovery.

Decision	Number of injuries				
	No injuries	Minor	Major	Fatal	Total
Stayed on the type	36	18	28	0	82
Converted to a different type	8	21	43	0	72
Resignation from flying	0	1	55	71	127
Total	44	40	126	71	281

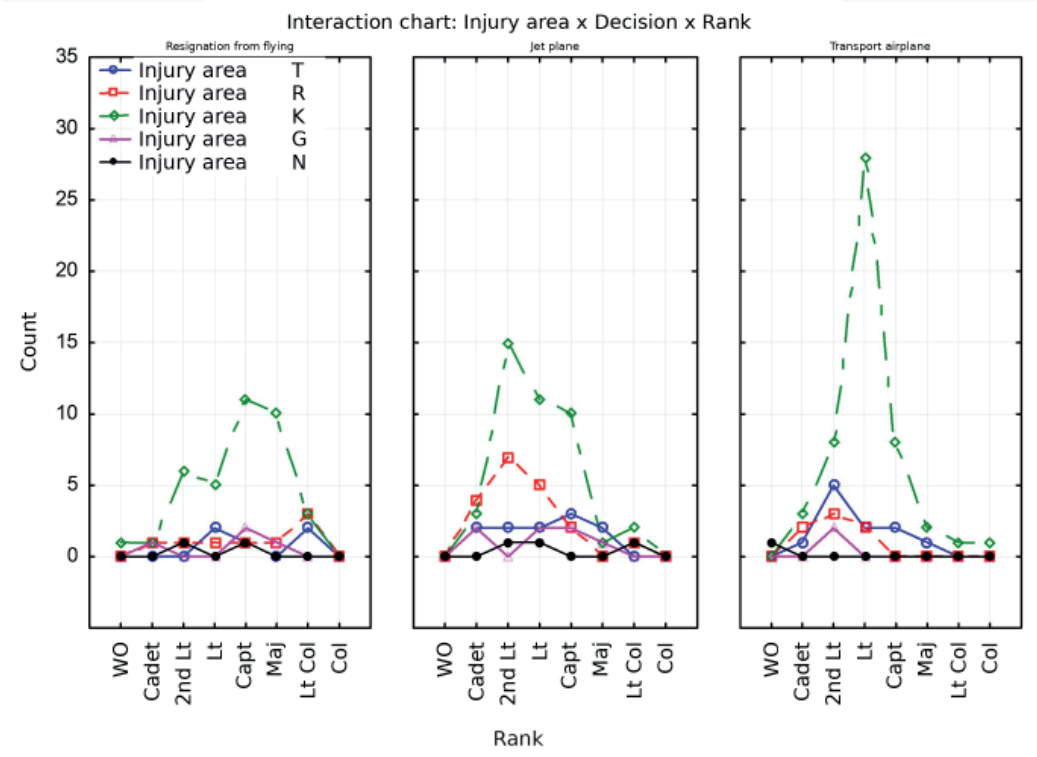


Fig. 5. The relationship between the area of injury, the decision made after being ejected, and military rank.

injury area – T: $\chi 2 = 15.242$ df = 14 p = 0.362

injury area – R: $\chi 2 = 12.419$ df = 14 p = 0.573

injury area – K: $\chi 2 = 40.517$ df = 14 p = 0.0002

injury area – G: $\chi 2 = 14.935$ df = 14 p = 0.383

injury area – N: $\chi 2 = 9.500$ df = 14 p = 0.798

of 21 pilots. They were assigned to transport planes and helicopters. One pilot's incapacity was due to a psychological issue, which is why he was permanently barred from flying any aircraft or helicopters. Pilots with serious injuries made up the largest group, numbering 126 people. Only 28 of them returned to flying missions in jet aircraft equipped with ejection seats. A total of 43 pilots were transferred to transport aircraft and helicopters, including 11 pilots who had ended their operational careers as fighter pilots a few days after ejecting and were subsequently transferred to multi-crew transport aircraft to occasionally perform flight duties as co-pilots.

In the graph in Fig. 5. the study examined the relationship between the location of the injuries sustained and the pilots' decisions regarding their continued suitability to fly jet or transport aircraft, as well as their military rank.

An analysis of the relationship between the location of the injury and the subsequent decision regarding fitness for flight showed statistical significance only for injuries to the limbs (K): $\chi^2 = 40.517$; df = 14; p = 0.0002. For the other body regions analyzed, the correlations did not reach statistical significance.

In addition, an analysis was conducted of data from the international literature on military

ejection from other air forces, in order to place our own results within a broader epidemiological, technological, and clinical context. The injury rates for the three most commonly used ejection seat systems are as follows:

ACES II/ACES 5 (USA) seat [3,5,19]
- used in the F-15, F-16, A-10, B-1B, B-2,
- a two-stage, computer-controlled rocket system,
- common injuries: compression fractures of L1–L4, shoulder girdle injuries, and muscle attachment tears in the cervical spine.

K-36DM Armchair (Russia) [4.19]
- used in the MiG-29, Su-27, Su-57, Tu-160,
- powerful powder charge and automatic mechanisms,
- distinctive settling profile, extended separation time,
- common injuries: sternum fractures, head and neck injuries resulting from ejection at low altitudes, intracranial hemorrhages (due to improper head positioning).

The K-36DM seats are considered among the most reliable, but the risk of injury remains high due to high initial accelerations.

Martin-Baker ejection seats (Europe, NATO) [14,19]
- used in the Tornado, Typhoon, Hawk, F-35B, Gripen,
- Mk.10–Mk.18 versions with SMART SEAT systems,
- advanced body position stabilization and condition-dependent automation,
- common injuries: pelvic injuries and rotational hip joint injuries, especially among pilots with a low BMI.

KM-1, KM-1M, KS-3, KS-4, KK-1, KK-2 seats (Soviet-made, used by the Polish Air Force) [18,19,27-29]
- used in the MiG-15, MiG-17, MiG-19, MiG-21, MiG-23, Su-7, Su-20, Il-28,
- powerful powder charge and automatic mechanisms,
- distinctive settling profile, extended separation time,
- common injuries: sternum fractures, head and neck injuries resulting from low-altitude ejection, spinal fractures (L-5, S-1, Th-8), and limb injuries.

DISCUSSION

The ejection seat remains a rescue procedure of very high operational value, but it is also a biomechanically demanding intervention. In the analyzed data covering 281 ejection incidents in the Polish Air Force (PAF) between 1951 and 2025, there were 44 cases with no injuries (15.7%), 40 cases of minor injuries (14.2%), 126 cases of serious injuries (44.8% of all ejection incidents; 60.0% of survivors), and 71 fatalities (25.3%). This distribution, shown in Fig. 1 and in Table 3. indicates that survival alone cannot be the sole measure of an evacuation system's effectiveness; the severity of injuries and the pilot's continued ability to perform their duties are equally important.

In a meta-analysis by Epstein et al. [6], which included 14 studies and 1,710 ejection incidents, the cumulative mortality rate was 10.5%, and the incidence of severe injuries was 29.8%; in the same study, Israeli Air Force data from 1990–2019 reported 37 ejection incidents, a 5.4% fatality rate, and an 18.9% rate of severe injuries. In the RAF analysis [9], which included 232 cases, the overall survival rate was 89.2%, 95.7% for ejection within the operational envelope, and 23.8% outside the envelope, with a 29.4% incidence of spinal fractures. The wide variation in results is also confirmed by the authors of other studies. In Royal Australian Air Force experiments conducted between 1951 and 1992, Newman [20] reported a 8.3% fatality rate and a 50.0% rate of serious injuries, while Sandstedt [25], in data from the Swedish Air Force covering the years 1967–1987, described a very low fatality rate despite a still significant percentage of injuries following ejection. Visuri and Aho [30], however, demonstrated that injuries related to the use of ejection seats remained a significant problem in aviation medicine among Finnish pilots as well. Compared to these figures, the mortality rate in the PAF data is high, which most likely reflects the long observation period, the prevalence of older ejection seats, and the high proportion of incidents occurring at very low altitudes. At the same time, comparisons between series should be interpreted with caution due to differences in definitions, aircraft types, seat generations, flight phases, and the availability of medical records.

In the ejection incidents analyzed, the most significant clinical outcome is the prevalence of spinal injuries. The spine was the most common site of injury: 19 minor injuries and 98 serious injuries, accounting for 77.8% of all serious injuries (Table 2). A total of 262 individual vertebral fractures were documented (Table 1). Most frequently, they involved L-5 (n = 37), S-1 (n = 34), C-5, and Th-8 (n = 21 each). This finding confirms the importance of axial overloads and the compressive mechanism, although the L5/S1 location differs from some of the literature, which

more frequently describes the thoracolumbar segment. For example, in a study by Manen et al. [13] 42% of pilots suffered spinal fractures following ejection, mainly simple compression fractures of the thoracic spine, whereas in the study by Sommer et al. [26] The incidence of spinal injuries was 56.3%, and that of fractures was 33.0%. Rotondo [23] also described the importance of biomechanics in spinal injuries resulting from ejection, emphasizing the need to integrate injury mechanism analysis with diagnosis, long-term follow-up, and prevention. The variation in the location of spinal fractures in the PAF data may be related to differences in how injuries are coded, the nature of historical records, and the role of the landing phase and secondary injuries sustained after exiting the seat. The final injury pattern may result from the combined effects of axial loads, airflow dynamics, the stability (or lack thereof) of the restraint systems, parachute deployment, and landing. Assessing the relative contribution of these mechanisms requires a detailed analysis, which, however, is beyond the scope of this study.

Spinal injuries are significant not only from a diagnostic perspective but also from an assessment perspective. The data presented in Table 7 show that, of the 210 surviving pilots, only 82 remained on their previous aircraft type, 72 were transferred to a different type, and 56 stopped flying. Among the pilots who suffered serious injuries, only 28 out of 126 returned to active duty in their previous aircraft equipped with ejection seats, while 43 were reassigned and 55 gave up flying. These data support the conclusion that ejection is not only a life-saving event but also a potential turning point in a pilot's career. From the perspective of aviation medicine, long-term consequences are also significant. Kozicki [8] described the long-term health effects of ejection on military pilots, including chronic pain and physical limitations, while Fowlie and Aveline [7] highlighted the potential psychological consequences of ejection, rescue operations, and rehabilitation. Therefore, the post-ejection assessment should not be limited to identifying acute injuries, but should include neurological, orthopedic, rehabilitative, and psychological evaluations.

The type of ejection seat proved to be a key factor in determining the outcome of an emergency evacuation from an aircraft. The highest number of ejection incidents was recorded for the KK-1 and KK-2 seats (Table 3). These groups also had the highest number of serious injuries and deaths: 36 serious injuries and 29 deaths for KK-1, and 21 serious injuries and 11 deaths for KK-2. This result is consistent with technological advancements in rescue systems, where older seats ensured survival in some incidents but were less effective at controlling the acceleration profile, body stabilization, and separation sequence. The impact of the entire rescue sequence on the injury profile is also evident in McCarthy's analysis [15] of USAF ejection incidents during takeoff and landing between 1973 and 1985. This is important when interpreting PAF data, as the final injury outcome may have depended not only on the ejection itself, but also on the phase of flight, body position, uncontrolled limb movements, and secondary injuries sustained during descent and landing. In more recent models, the number of ejection incidents in the PAF was lower, so comparisons should be made with caution. Nevertheless, the data in Table 3 support the argument that upgrading seats and evacuation procedures is one of the key strategies for reducing injuries.

The strongest association with the risk of death was related to the height of the ejection. In the category of less than 150 m, there were 40 deaths out of 48 cases, representing a mortality rate of 83.3% (Table 4). At altitudes between 151 and 300 meters, deaths occurred in 15 out of 38 cases (39.5%), while at altitudes above 1,000 meters they were rare. This result is consistent with Newman's study [21], in which the survival rate was 51.2% for 562 low-altitude ejections, while it was 91.4% for ejections above 500 ft (152 m). In contrast, the risk of death during an ejection below 500 feet was about ten times higher. The importance of the decision threshold is also confirmed by the studies of Callaghan and Irwin [1,2], which analyzed the decision to eject and the impact of the designated decision altitude on the effectiveness of the evacuation. In the results presented, altitude is therefore the strongest practical argument for training pilots to make a quick decision to evacuate the aircraft and for minimizing decision-making delays. Training should cover not only familiarity with the technical procedure, but also repeated practice of the criteria for aborting aircraft rescue attempts, because in low-altitude scenarios, even a brief delay can cause the ejection to occur beyond the range within which the seat-parachute sequence can be fully deployed.

An analysis of the relationship between ejection speed and injuries showed (Table 5) that the highest number of severe injuries was recorded in the 401–550 km/h range (n = 49), but the highest number of deaths occurred in the 251–400 km/h range (n = 28), and the highest percentage

of deaths was in the group below 250 km/h (13/27; 48.1%). This does not confirm a simple, linear increase in mortality with speed. It is more likely that the aircraft's speed, altitude, flight phase, and orientation are all contributing factors. A similar nonlinear relationship between flight parameters and ejection performance is suggested by Milanov's analysis [16] of Bulgarian experiments conducted between 1953 and 1993. The same speed range may pose different risks depending on altitude, flight path angle, aircraft roll or pitch, the pilot's condition, and the time available to stabilize the aircraft after ejection. A lower speed may indicate a takeoff, approach, or critical phase near the ground, and thus insufficient time for a full seat-to-parachute sequence.

Among deaths resulting from ejection, human error was a factor in 46 out of 71 cases (64.8%). This does not automatically mean the pilot is at fault. In aviation, the human factor also includes time pressure, loss of spatial orientation, misjudgment of the ability to regain control, task overload, and delayed ejection decisions. In Miles's study [17], delayed ejection decisions were more common, among other things, in cases involving higher flight hours and incidents caused by mechanical or human-factors issues, which the author interpreted as a possible result of overconfidence or attempts to save the aircraft. A systemic approach to this problem is consistent with Reason's classic model [22], in which operator error is often the final link in a chain of events involving organizational conditions, perceptual limitations, task pressure, and system design. The PAF data analyzed thus support the need for repeated training on decision thresholds and ejection procedures in scenarios of increasing severity. This training should be combined with the development of procedures that reduce ambiguity in situations and limit the tendency to attempt to save an aircraft for an excessively long time.

The results of the analysis confirm the need for a consistent medical protocol following ejection. Since spinal injuries are the most common (Tables 1 and 2), every pilot who has been ejected should be treated as a patient with a potential axial injury until such an injury has been ruled out. This is well-supported by the literature. Epstein et al. [6] emphasized that, given the high incidence of spinal fractures, spinal stabilization and advanced imaging are necessary, and Manen et al. [13] demonstrated that some fractures were missed or underestimated on conventional X-rays. In practice, this argues in favor of a low threshold for CT/MRI scans, neurological evaluation, and subsequent orthopedic and neurosurgical follow-up. The medical report should also take into account head and neck injuries, even though, in the data analyzed, they accounted for a smaller proportion of severe injuries than spinal injuries. Rowe and Brooks [24] described head and neck injuries sustained during ejection from Canadian Forces aircraft, highlighting the significance of airflow, equipment, and impacts during the ejection sequence. This justifies the assessment of the helmet, oxygen mask, face, eyes, and cervical spine, as well as the documentation of symptoms of concussion, visual disturbances, or soft tissue injuries.

Limitations of the study

The limitations of this study include the retrospective nature of the analysis, the long observation period spanning several generations of aircraft and seats, the variability in medical records, and the lack of uniform definitions for "minor" and "major injury" throughout the entire period from 1951 to 2025. There is also a lack of exposure metrics, such as the number of flight hours on a given aircraft type and seat, as well as comprehensive anthropometric and physiological data. Therefore, the results presented here do not constitute a comprehensive causal analysis of all injury mechanisms.

SUMMARY AND CONCLUSIONS

In summary, ejection is a highly effective life-saving procedure, but it carries a predictable injury profile characterized primarily by spinal injuries, with head, neck, and limb injuries also being significant – particularly in situations involving high speed, low altitude, loss of control of the aircraft, and suboptimal body position.

Older seat types, particularly the KK-1 and KK-2, were associated with the highest number of serious injuries and fatalities, which supports recommendations to upgrade rescue systems and evacuation training. In addition, it was noted that the severity of the injuries had a significant impact on the pilots' future careers: only 28 of the 126 pilots with severe injuries remained on the same type of aircraft.

Anthropometric factors (height, body weight, BMI) may influence the risk of various types of injuries; however, these relationships are complex and result from the interaction between the occupant, the seat, and flight parameters. The most promising approach to reducing severe consequences remains a holistic one, encompassing

the development of seat designs, rigorous training (including emergency simulations with training in decision thresholds and ejection procedures), the modernization of personal protective equipment, and highly specialized, standardized medical and rehabilitation care following evacuation.

AUTHORS' DECLARATION

Study Design: Marian Macander. **Data Collection:** Marian Macander. **Manuscript Preparation:** Marian Macander. The author declares that there is no conflict of interest.

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