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Appendix S1. Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	3
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	3
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	4
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	4
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	4
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	4
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	4
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	4-5
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	5
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	5
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	5
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	5-6
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	6

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	6
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	7-8
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	9-19
Limitations	20	Discuss the limitations of the scoping review process.	19-20
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	20
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	21

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.
** Where sources of evidence (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.*
† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with information sources (see first footnote).
‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.
§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).
From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

Appendix S2. Search strategy used for each of the Databases.

Database	Search Strategy
Pubmed	(("F-16 pilot*" OR "fighter pilot*" OR "military aviator*" OR "high-G pilot*" OR "jet pilot*") AND ("G-force tolerance" OR "high-G environment*" OR "G-induced loss of consciousness" OR "G-LOC" OR "anti-G straining maneuver*" OR "AGSM" OR "aerobic fitness" OR "strength training" OR "pilot conditioning" OR "G-suit*" OR "cockpit ergonomics" OR "physiological adaptation*" OR "aerospace physiology" OR "psychological training" OR "cognitive performance" OR "mental fatigue" OR "stress management") AND ("military aviation" OR "flight training" OR "aeronautical training" OR "aerospace medicine" OR "pilot training" OR "high-G exposure" OR "centrifuge training" OR "flight simulation"))
SPORTDiscus	("F-16 pilot*" OR "fighter pilot*" OR "military aviator*" OR "high-G pilot*" OR "jet pilot*") AND ("G-force tolerance" OR "high-G environment*" OR "G-induced loss of consciousness" OR "G-LOC" OR "anti-G straining maneuver*" OR "AGSM" OR "aerobic fitness" OR "strength training" OR "pilot conditioning") AND ("military aviation" OR "flight training" OR "aerospace medicine" OR "high-G exposure" OR "centrifuge training")

Database	Search Strategy
Web of Science	TS=("F-16 pilot*" OR "fighter pilot*" OR "military aviator*" OR "high-G pilot*" OR "jet pilot*") AND TS=("G-force tolerance" OR "high-G environment*" OR "G-induced loss of consciousness" OR "G-LOC" OR "anti-G straining maneuver*" OR "AGSM" OR "aerobic fitness" OR "strength training" OR "pilot conditioning" OR "G-suit*" OR "cockpit ergonomics" OR "physiological adaptation*" OR "aerospace physiology" OR "psychological training" OR "cognitive performance" OR "mental fatigue" OR "stress management") AND TS=("military aviation" OR "flight training" OR "aeronautical training" OR "aerospace medicine" OR "pilot training" OR "high-G exposure" OR "centrifuge training" OR "flight simulation")
Scopus	TITLE-ABS-KEY(("F-16 pilot*" OR "fighter pilot*" OR "military aviator*" OR "high-G pilot*" OR "jet pilot*") AND ("G-force tolerance" OR "high-G environment*" OR "G-induced loss of consciousness" OR "G-LOC" OR "anti-G straining maneuver*" OR "AGSM" OR "aerobic fitness" OR "strength training" OR "pilot conditioning" OR "G-suit*" OR "cockpit ergonomics" OR "physiological adaptation*" OR "aerospace physiology" OR "psychological training" OR "cognitive performance" OR "mental fatigue" OR "stress management") AND ("military aviation" OR "flight training" OR "aeronautical training" OR "aerospace medicine" OR "pilot training" OR "high-G exposure" OR "centrifuge training" OR "flight simulation"))
Air University Library Index to Military Periodicals	("F-16 pilot*" OR "fighter pilot*" OR "military aviator*" OR "high-G pilot*" OR "jet pilot*") AND ("G-force tolerance" OR "high-G exposure" OR "G-induced loss of consciousness" OR "G-LOC") AND ("anti-G straining maneuver*" OR "AGSM" OR "aerobic fitness" OR "pilot conditioning") AND ("military aviation" OR "flight training" OR "aerospace medicine" OR "centrifuge training")
JSTOR Security Studies Collection	("fighter pilot*" OR "military aviator*" OR "high-G pilot*") AND ("G-force tolerance" OR "high-G environment*" OR "G-induced loss of consciousness") AND ("G-suit*" OR "cockpit ergonomics" OR "physiological adaptation*" OR "psychological training") AND ("military aviation" OR "flight simulation" OR "aerospace medicine")
Military & Government Collection (EBSCOhost)	("F-16 pilot*" OR "fighter pilot*" OR "military aviator*") AND ("G-force exposure" OR "high-G environment*" OR "G-LOC") AND ("AGSM" OR "aerobic fitness" OR "pilot endurance" OR "G-suit*") AND ("military aviation" OR "aerospace medicine" OR "operational performance")
Military Database (ProQuest)	("fighter pilot*" OR "military aviator*" OR "high-G pilot*") AND ("G-force tolerance" OR "G-induced loss of consciousness" OR "AGSM training") AND ("psychological resilience" OR "aerobic training" OR "cognitive adaptation") AND ("military aviation" OR "fighter pilot training" OR "flight simulation")

Appendix S3. Excluded articles and reasons for exclusion (n = 24).

Citation	Study	Reason for exclusion
Schreuder 1966	Medical aspects of aircraft pilot fatigue with special reference to the commercial jet pilot	Focus on commercial pilots, not fighter pilots.
Wood 1987	Development of methods for prevention of acceleration induced blackout and unconsciousness in World War II fighter pilots. Limitations: present and future.	Historical study that may not reflect modern conditions and strategies.
Buckley et al., 2018	Pelvic Organ Prolapse in a Fighter Pilot with Alpha-1 Antitrypsin Deficiency	Isolated case report that does not meet the review criteria.
Yeow et al., 2002	An expert system for generation of anti-G control schedule for jet fighter pilots	Possibly more focused on automated systems than on human G-force tolerance.
Lauritzsen et al., 2003	Pressure breathing in fighter aircraft for G accelerations and loss of cabin pressurization at altitude - a brief review	Brief review, not an original study.
Catrambone et al., 2013	Vasodilation Associated with Supplement Use: Potential Concern for Military Aviators	Focuses on the effects of vasodilator supplements, with no direct relation to G-force tolerance.
Lange et al., 2013	Centrifuge-Induced Neck and Back Pain in F-16 Pilots: A Report of Four Cases	Case reports that do not meet the inclusion criteria.

Citation	Study	Reason for exclusion
Yajima et al., 1994	Human cardiovascular and vestibular responses in long minutes and low +gz loading by a short arm centrifuge	Low G-force simulation without a focus on flight.
Tu et al., 2022	A Rare Case of Rib Fractures During Centrifuge Training	Isolated case, does not meet the criteria.
Kampel et al., 2015	Scrotal Hematoma Precipitated by Centrifuge Training in a Fighter Pilot with an Asymptomatic Varicocele	Case report, does not fit the review.
Khan et al., 2002	Prediction of electrical impedance parameters for the simulated leg segment of an aircraft pilot under G-stress	Focus on computational simulation, excluded by criteria.
Zhang et al., 1991	Experimental-verification of effectiveness and harmlessness of the qigong maneuver	Focus on Qigong techniques, without relevant military validation for G-force tolerance.
Maturo et al., 2006	Vocal cord paralysis in a fighter pilot	Isolated case, does not meet inclusion criteria.
King et al., 1991	Flight psychology at sheppard air-force base	Focus on flight psychology, not specifically on G-force tolerance.
Khatua et al., 2019	Aeromedical Decision Making in Internal Jugular Phlebectasia	Aeromedical decisions for a specific condition, not relevant to the review topic.
Guillaume et al., 1997	Effects of perfusion on the mechanical behavior of the brain exposed to hypergravity	Focus on the mechanical behavior of the brain without direct connection to fighter pilots.
Caldwell et al., 2004	Modafinil's effects on simulator performance and mood in pilots during 37 h without sleep	Focus on sleep deprivation and stimulants, with no direct link to G-force tolerance.
Leinonen et al., 2021	Normobaric hypoxia training in military aviation and subsequent hypoxia symptom recognition	Focus on hypoxia training, which is not a primary factor in G-force tolerance.
Tan et al., 2012	Positional and Rotational Stability of the Toric Phakic Intraocular Lens Under High +Gz Environments	Study on intraocular lenses, not relevant to the review.
Florence et al., 2005	Psychostimulants and G tolerance in rhesus monkeys: Effects of oral modafinil and injected caffeine	Study on animal models, which does not fit the review criteria.
Topbas et al., 2024	Relationships among barodontalgia prevalence, altitude, stress, dental care frequency, and barodontalgia awareness: a survey of Turkish pilots	Focus on dental issues, unrelated to G-force tolerance.
Maltez-Laurienti et al., 2021	Exploring Neurocognitive Performance Differences in Military Aviation Personnel	Focus on general neurocognitive performance, with no direct link to G-force resistance.
Webb et al., 1991	Unpredictability of fighter pilot G tolerance using anthropometric and physiologic variables	Excluded for not involving military pilots in a real-flight context, per eligibility criteria
Luu et al., 2023	Assessment of 'G Endurance' Tolerance of Healthy Males on Modafinil After Extended Period of Wakefulness	Excluded for not focusing on military pilots in operational flight settings
Burton 1989	Human Physiological Limitations to G in High-Performance Aircraft;	Excluded for not presenting original data on military pilots in real-flight conditions
Yan et al., 2010	Application of new human centrifuge in military aviation medicine	Excluded for focusing on equipment application rather than G tolerance data from military pilots in real-flight conditions

Appendix S4. Details of studies and information relevant to G-Force Performance in Female Pilots

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Chelette et al., 1998: Female performance in the high g environment: an overview of centrifuge research 1996-1997	Conference paper	Participants: Men and women (exact number not specified). Exposure: Several months of high-G environment exposure. Details: Both genders trained for operations in high-G conditions.	Main Task: Simulated air-to-air combat missions. Additional Tests: Cardiac function, muscular strength, cerebral oxygen saturation. Conditions: Sustained exposure to high gravitational forces (high-G).	• Cardiac function • Muscular strength • Cerebral desaturation • Performance during simulated missions • Menstrual cycle effects (in women)	• Gender (male vs female) • Menstrual cycle (phase, effects on performance and progression) • Physiological adaptation to high-G environment • G-force endured during simulations	• No adverse cardiac effects observed in either gender after months of G-exposure. • Both men and women maintained muscular strength post-exposure. • Women showed less cerebral desaturation than men under high-G. • Women performed slightly worse than men during simulated combat missions, although they withstood similar G-forces. • No effect of the menstrual cycle on mission performance or completion rates. • High-G exposure had no impact on menstrual cycle progression. • Conclusion: Nothing found in the study suggests that women should not fly high-performance aircraft.
Zhang, 1999: Cognitive performance and physiological changes in females at high G while protected with COMBAT EDGE and ATAGS	Observational Study (Cross-sectional Study)	The study involved six female centrifuge subjects. These participants were likely selected to represent female fighter pilots who operate aircraft like the F-16 and F-15, which utilize the COMBAT EDGE system for positive pressure breathing under G (PBG) protection	Participants completed 3-minute simulated aerial combat sorties on the Dynamic Environment Simulator. This setup was used to mimic the high G conditions experienced during actual flight operations, allowing for a controlled comparison of the two anti-G suits	The study measured several physiological and performance outcomes, including: • Heart rate • Percent arterial oxygen saturation (%SaO_2)	The study considered the differences in suit design and fit, noting that the ATAGS were prototype suits and not custom-fitted to the female subjects. This factor could influence the comfort and effectiveness of the suits	• No significant differences in performance or EMG were observed between the two suit conditions. • The ATAGS suit resulted in significantly lower %rSO_2 and %SaO_2, as well as a lower heart rate during the last minute of G exposure compared to the STD suit. • Subjects reported better G tolerance with the ATAGS suit but found it more uncomfortable, likely due to the prototype nature and lack of custom fitting

G - Gravitational force (acceleration due to gravity); COMBAT EDGE - Combined Advanced Technology Enhanced Design G-Ensemble; ATAGS - Advanced Technology Anti-G Suit; STD - Standard CSU 13 B/P anti-G suit; PBG - Positive Pressure Breathing under G; %SaO_2 - Percent Arterial Oxygen Saturation; %rSO_2 - Percent Regional Cerebral Tissue Oxygen Saturation; EMG – Electromyography.

Appendix S5. Details of studies and information relevant to Physiological and Anthropometric Factors Related to G-Tolerance

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Harel et al., 2024: Height and blood pressure as predictors of g-loc risk in jet pilots: insights from the Israeli air force	Observational Study (Cohort Study)	Sample Size: 15 G-LOC cases, each matched with one control. Matching Criteria: Same age and squadron. Demographics: All male; average age 23.4 ± 5.58 years. Groups: G-LOC group vs. matched control group.	Environment: Operational flight conditions (real jet missions). Variables Observed: G-level at G-LOC onset, aircraft control status ("holding the stick"), prior symptoms, duration of incapacitation. Participants: Active IAF pilots and cadets under high-G conditions.	• Height • Systolic blood pressure • G-level that triggered G-LOC • Control over the aircraft during event • Flying experience • Symptoms preceding G-LOC • Duration of incapacitation	• Physical attributes: Height, blood pressure. • Experience: Cadets vs. aircrew. • Operational role: Pilots actively controlling the aircraft vs. not. • Flight conditions: Variations in G-force exposure during real missions.	• Height: Pilots in the G-LOC group were significantly taller (183.93 cm) than controls (177.47 cm) – $p < 0.001$. • Blood Pressure: G-LOC group had significantly lower systolic blood pressure (123 mmHg vs. 128.4 mmHg in controls) – $p = 0.03$. • G Tolerance: Higher G-levels were needed to induce G-LOC in experienced aircrew and those who were in control of the aircraft. • Reinforcement: Findings align with prior centrifuge studies, though this was based on real in-flight G-LOC events. • Conclusion: Taller stature and lower blood pressure may be risk factors for G-LOC, suggesting the need for personalized risk assessment and training adaptations in high-G environments.
Park et al., 2015: Unpredictability of Fighter Pilots'G Duration Tolerance by Anthropometric and Physiological Characteristics	Observational Study (Cross-sectional study)	• Subjects: Fighter pilot trainees. • Sample Size: Not explicitly stated in the preview, but the study analyzes a cohort undergoing high-G centrifuge testing. • Demographics: Likely includes adult males of typical military age, specific numbers and characteristics not visible.	• Setting: Human centrifuge simulations. • Activity: Exposure to sustained +Gz acceleration to simulate flight conditions. • Procedure: Participants were subjected to G-forces to measure their G duration tolerance (i.e., how long they can sustain high G before symptoms or failure).	• Main Outcome: G duration tolerance (time under high G before losing performance or vision). • Additional Metrics: • Anthropometric data (e.g., height, weight, body composition) • Physiological characteristics (e.g., heart rate, blood pressure, fitness indicators)	• Individual differences: Variability in anthropometric and physiological data. • Environmental/Training Factors: All participants underwent standard training; differences were observed despite this control. • Unpredictability Theme: Highlighted that standard metrics may not reliably predict G duration tolerance.	• Primary Insight: Anthropometric and physiological characteristics alone are insufficient predictors of G duration tolerance. • Variability: Considerable individual variation was observed, suggesting other unexplored factors may play a role (e.g., neurological, psychological, genetic). • Implication: Pilot selection and training should not overly rely on physical metrics for predicting high-G performance.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Tu et al., 2020: Roles of Physiological Responses and Anthropometric Factors on the Gravitational Force Tolerance for Occupational Hypergravity Exposure	Observational Study (Cross-Sectional Study)	Participants: 873 Male student pilots from the Air Force Academy in Taiwan undergoing intermediate high-G training. Exclusions: Trainees without 7.5G profile attempt (n=7), incomplete data (n=2), or lost HR signal (n=19). Final Analyzed Group: 873 trainees. Demographics: Young males, around 23.5 years old.	Training Method: Centrifuge simulation replicating high-G flight conditions. G-Profile Tested: Rapid onset to 7.5G sustained for 15 seconds. Steps: • Gradual onset run (relaxed and straining G tolerance evaluation). • Rapid onset to 6G for AGSM practice. • Main test: Rapid onset to 7.5G for 15 seconds. • Additional 6G postures to simulate air combat. Rest Intervals: 2 minutes between profiles at 1.4G idle run.	Primary Outcome: Success or failure to complete 15 seconds at 7.5G (G-tolerance). Physiological and Anthropometric Metrics: • Heart rate (HR) at various stages. • Body Mass Index (BMI). • Relaxed G Tolerance (RGT). • Straining G Tolerance (SGT). • AGSM (Anti-G Straining Maneuver) score.	HR Increase Percentage: Calculated as peak HR during the first 1–5 seconds of the 7.5G profile divided by HR before exposure. AGSM Proficiency: Assessed based on 4 components of correct breathing and muscle straining technique. Baseline physiological state, previous G-exposure, psychological stress.	HR Response: A smaller increase in HR during the first 1–5 seconds of 7.5G was strongly associated with failure (adjusted odds ratio: 9.91). BMI: Higher BMI was positively associated with success (each unit increase reduced failure risk by 21%). RGT and SGT: Lower thresholds (<4.5G and <6.5G, respectively) were significantly linked to failure. AGSM Score: Borderline predictor; trainees with scores <8 had higher failure rates, but it was less predictive in multivariate analysis. Conclusion: G-tolerance is strongly affected by early HR response, BMI, and individual G tolerance levels. Rapid baroreflex activation (HR rise) may be critical in preventing GLOC.
Sundblad et al., 2016: The arterial baroreflex and inherent G tolerance	Observational study (Cohort study)	Sixteen healthy male subjects participated, divided into two groups based on G tolerance: high G tolerance (H group) and low G tolerance (L group). The H group had a G tolerance of more than 5.5 G, while the L group had less than 4.2 G. The average age was 27 years, with slight differences in body mass and height between the groups	The G tolerance was tested using a gradual onset rate (GOR) in a human-use centrifuge. The G load increased by 0.1 G/s until vision impairment occurred. The carotid baroreflex was assessed using a neck chamber device to vary pressure over the neck, simulating different G conditions	The study measured heart rate (HR) and arterial pressure (AP) responses to neck pressure stimulation. Baroreflex sensitivity was evaluated by fitting a polynomial function to the response curves. The study also assessed the latency of AP responses and the differences in baroreflex sensitivity between groups and postures	The study controlled for posture by measuring responses in both supine and upright positions. It also considered the hydrostatic pressure difference between the heart and neck when calculating carotid distending pressure (CDP)	The H group showed a more pronounced increase in AP in response to hypotensive stimuli in the upright position compared to the L group, indicating stronger vasoconstriction. There were no significant differences in baroreflex sensitivity or chronotropic responses between the groups, suggesting that vascular responses, rather than cardiac responses, are more critical for G tolerance. The study concluded that reflexive vasoconstriction and the speed of vascular baroreflex during orthostatic stress are linked to higher G tolerance.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Cao et al., 2012: Visual Symptoms and G-Induced Loss of Consciousness in 594 Chinese Air Force Aircrew-A Questionnaire Survey	Observational Study (Cross-sectional study)	Sample Size: 594 aircrew members. Demographics: All healthy males, aged 22–53, height 163–183 cm, weight 55–105 kg. Roles: 524 pilots (88.2%), 18 weapon–system operators (3.0%), 52 navigators (8.8%). Aircraft Types Represented: Fighters (52.9%), trainers (11.3%), helicopters, transporters, etc.	Method: Retrospective survey conducted during aircrew vacation; no live G-exposure during the study. Questionnaire Components: Part I: Demographics and flying experience. Part II: Details about G-related symptoms, physical training habits, and attitudes toward G-training. Context: Assessed real-life +Gz exposure experiences during operational and training flights.	Symptoms Reported: • Visual blurring: 18.5% • Greyout: 38.9% • Blackout: 18.7% • G-LOC: 8.2% Flight Conditions: G exposure between +3 to +9 Gz, mostly between +5 and +5.9 Gz. Incident Contexts: Rapid onset acceleration, aerobatics (95.5%), loops, and other maneuvers. Training Evaluation: Anti-G suit usage, AGSM performance, centrifuge training, and physical training habits.	Experience: Symptoms most common in pilots with 250–1,000 total flight hours and <500 hours on type. Equipment & Maneuvers: • 78.5% wore anti-G suits. • 43.1% performed AGSM during incidents. • 73.1% used oxygen masks. • Only 15.8% used positive pressure breathing. Physical Training: • 97.3% engaged in regular exercise. • 87.1% focused on aerobic training, only 12.9% on resistance/anaerobic training.	• High prevalence of visual symptoms and G-LOC, particularly in young, inexperienced pilots. • G-LOC events occurred even at moderate G-levels (+4 to +6.9 Gz). • Low on-type flight hours were a strong predictor of G-LOC. • Poor G-awareness was identified; many aircrew did not use AGSM despite acknowledging its importance. • Centrifuge training was undervalued (only 59.4% saw it as beneficial), despite its proven role in other air forces. • Physical fitness routines focused too much on aerobic exercise, which may not improve G-tolerance; anaerobic training was rare. • Recommendations: Improve AGSM training, integrate early centrifuge training, educate on G-awareness, and adopt balanced physical training programs.
Gillingham, 1987: G-tolerance standards for aircrew training and selection	Observational study (Descriptive Study)	Subjects: Fighter pilots, trainees, non-flying aircrew, and aeromedical patients. Demographics: Includes both male and female participants (e.g., 213 men, 24 women in one test group). Cohorts: • Active USAF fighter aircrew (F-15, F-16). • LIFT (Lead-In Fighter Training) students. • Medically referred cases for in-flight GLOC.	Testing Method: Human centrifuge, applying +7Gz or +8Gz for 15 seconds. Conditions: • Upright or F-16-configured seat (30° reclined). • Full anti-G suit worn. • Mandatory performance of Anti-G Straining Maneuver (AGSM). Pass Criteria: Must sustain the G profile without losing peripheral vision or consciousness.	Primary Measure: G-tolerance capability (pass/fail at 7G or 8G for 15 seconds). Additional Observations: • Loss of consciousness. • Peripheral vision loss. • AGSM effectiveness. • Training impact and retention. • Cardiovascular screening (for failures).	Aircraft Configuration: Standard vs. F-16-configured centrifuge seats. Training History: Active aircrew vs. trainees or medically disqualified individuals. Medical Evaluation: Required for those who fail the G profile more than once. Policy Adoption: NATO STANAG 3827 and ASCC ADV PUB 61/26A referenced.	The 7G for 15 seconds standard is adequate and attainable for nearly all active fighter aircrew. 99% of USAF active fighter pilots passed. 80% of non-flyers and 88% of women passed the profile. Lower G-tolerance is predictive of risk for G-LOC in flight. Failure at 6G does not reliably predict in-flight safety—7G is the minimum effective threshold. Centrifuge training increases AGSM performance and overall safety. The author recommends formal implementation of G-tolerance standards for fighter pilot selection to prevent avoidable GLOC-related mishaps. Higher G-tolerance standards (e.g., 10G for ATF pilots) may be required in the future as aircraft become more capable.
Sundblad et al., 2014: G tolerance and the vasoconstrictor reserve	Observational Study (Cohort Study)	Sixteen healthy male subjects participated, divided into two groups: high G tolerance (H group) and low G tolerance (L group). The average age was 27 years for both groups, with differences in body mass and height. Subjects were selected based on their relaxed G tolerance, with specific thresholds for inclusion in the H and L groups.	The cold pressor test (CPT) involved immersing the left hand in cold water for 2 minutes, performed in both supine and upright positions. The G tolerance test was conducted using a human-use centrifuge to determine the G-level tolerance.	Heart rate (HR), mean arterial pressure (MAP), cardiac output (CO), total peripheral resistance (TPR), and stroke volume (SV) were measured. The study focused on the changes in these variables in response to the CPT in both postures.	The study was conducted in a climate-controlled laboratory, and subjects were instructed to avoid alcohol, coffee, and tobacco before the tests. The tests were performed at a consistent ambient temperature, and the order of CPT tests was balanced among subjects .	The high G tolerance group (H group) showed a larger vasoconstrictor reserve, indicated by a greater increase in TPR and MAP during the CPT, especially in the upright position. The low G tolerance group (L group) relied more on increasing CO to elevate MAP, particularly when standing. The study suggests that myogenic responsiveness in precapillary resistance vessels is a key determinant of relaxed G tolerance and may be reflected in the vasoconstrictor reserve capacity.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Eiken et al., 2012 G tolerance vis-à-vis pressure-distension and pressure-flow relationships of leg arteries.	Observational Study (Cohort Study)	The study included two groups of subjects: High G tolerance group (H): 7 subjects with a relaxed G tolerance of 6.6 ± 0.8 G. Low G tolerance group (L): 8 subjects with a G tolerance of 3.9 ± 0.3 G. Both groups were matched for gender, age, weight, height, and resting arterial pressure.	The subjects were placed supine in a pressure chamber with one lower leg protruding outside. Intravascular pressure in the blood vessels of the outside leg was increased by stepwise raising the chamber pressure to 240 mmHg.	Diameter and flow in the posterior tibial artery were measured using ultrasonographic/Doppler techniques. Pressure-induced increments in arterial diameter and flow were recorded.	The study controlled for variables such as gender, age, weight, height, and resting arterial pressure to ensure that differences in G tolerance were not due to these factors.	The low G tolerance group (L) showed more pronounced increases in arterial diameter (14.1 ± 4.2%) and flow (32 ± 21 ml/min) compared to the high G tolerance group (H), which had increases of 1.7 ± 5.0% and 1.6 ± 25 ml/min, respectively. The pressure thresholds for these increments were lower in the L group by 52 and 48 mmHg, respectively. There were negative correlations between G tolerance and the increments in diameter and flow, suggesting that individuals with higher G tolerance have stiffer precapillary leg vessels.
Shin, S.-H. (2018) A Correlation Pilot-Study of F-15/16 Pilots' ACTN-3, G-tolerance, and Body Compositions	Observational study (Cross-sectional study)	The study involved 21 male F-15/16 pilots with an average age of 29.3 years, height of 173.5 cm, and weight of 78.6 kg. The participants were selected voluntarily and the study was approved by an institutional review board.	The exercise protocol involved a G-test where pilots were subjected to 9 Gs for 15 seconds. This test was used to measure G-tolerance based on the mean breath cycle duration.	The primary outcomes measured were the ACTN-3 polymorphism types (RR, RX, XX), G-tolerance (measured by breath cycle during the G-test), and various body composition metrics such as muscle mass, fat percentage, and BMI.	The study also considered the potential impact of muscle mass and fat on G-tolerance, noting a positive trend with muscle mass and a negative trend with fat. The study highlighted the importance of body composition management for pilots, given their mean BMI was categorized as obesity.	No significant differences were found in G-tolerance and body compositions based on ACTN-3 polymorphism. However, the 'RR' genotype showed a potential advantage in G-tolerance, inferred from the longest mean breath cycle. The study suggests that more participants and longer G-test durations are needed to confirm the potential predominance of the 'RR' genotype in G-tolerance. The findings emphasize the need for body composition management education for pilots due to the observed trends and the importance of physical capabilities in modern fighter jet performance.
Shin, S., & Jee, H. 2019 Investigation on body composition and physical fitness of Korean Air Force pilots from 1975 to 2016	Observational Study (Retrospective Cohort Study)	The study involved 72 male Air Force pilots aged between 23 and 39 years. The participants were categorized based on their ACTN-3 genotype into three groups: 27 with RR type, 34 with RX type, and 11 with XX type.	The study did not specify a particular exercise protocol. Instead, it focused on measuring various aspects of physical fitness and body composition to assess differences based on genotype.	Body Composition: Six items were measured, including height, weight, body fat, bone-muscle mass, and BMI. Physical Fitness: Seven items were assessed, including grip strength, abdominal strength, leg strength, abdominal endurance, cardiopulmonary endurance, flexibility, power, agility, and balance	The study considered the ACTN-3 genotype as a key variable influencing body composition and physical fitness. The significance level for statistical analysis was set at p<0.05.	The RR genotype was associated with a significantly higher BMI compared to the XX genotype. In terms of physical fitness, the RR genotype showed significantly higher agility, muscle endurance, and power than the XX genotype. Conversely, the XX genotype demonstrated better cardiopulmonary endurance compared to the RR genotype. The study suggests that the RR genotype may be more suitable for pilots, indicating a potential link between genotype and optimal performance in aviation contexts.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
De Sá et al., 2023 Cardiovascular autonomic regulation in fighter pilots: Lessons from active standing tests	observational study (Cross-Sectional)	The study included 21 military personnel aged 20-34 years, consisting of 9 fighter pilots and 12 non-pilots. The groups were matched by age, maximal oxygen uptake (VO_2max), and body mass index (BMI) to ensure comparability	The protocol involved recording R-R intervals in three phases: • 15 minutes in the supine position at baseline (SUPbaseline). • A 45-minute prolonged active standing test divided into six 5-minute time frames (ORT1 to ORT6). • A 15-minute recovery period in the supine position (SUPrecovery).	Heart rate variability was analyzed using spectral analysis to obtain normalized low (LFn) and high (HFn) frequency components. The variations (ΔΔ) from baseline and recovery periods were calculated to assess changes in sympathetic and vagal modulation.	The study focused on the autonomic modulation of the heart, particularly the sympatho-vagal balance, during and after exposure to conditions simulating flight stress.	Fighter pilots exhibited a smaller change in sympathetic (ΔLFn) and vagal (ΔHFn) modulation during recovery compared to non-pilots. Both groups showed similar changes in autonomic modulation during the orthostatic stress phase compared to baseline, with no significant differences over time. The findings suggest that fighter pilots have a reduced vagal reentrance and lower sympathetic withdrawal during recovery after active standing, indicating an impact of flight on autonomic regulation.
Dos Santos Rangel et al., 2023 Neuro-Cardiovascular Responses to Sympathetic Stimulation in Fighter Pilots	Observational study (Cohort Study)	The study included 21 fighter pilots, 8 transport pilots, and 20 nonpilots. These groups were selected to represent varying levels of exposure to high G-forces and different flight experiences.	The exercise protocol involved a tilt test, during which beat-to-beat blood pressure and heart rate were recorded. This test was used to simulate conditions that challenge the cardiovascular system, allowing for the assessment of autonomic responses.	The primary outcomes measured were changes in mean arterial pressure (MAP) and heart rate variability indices during the tilt test. Additional outcomes included the analysis of areas under the curves for MAP, vagal modulation indices (rMSSD, pNN50, SDNN), heart rate, and sympathovagal balance (LF/HF).	Cardiorespiratory fitness and flight experience were considered as contextual variables. The study examined correlations between these variables and cardiac autonomic indices, such as vagal reserve and sympathovagal balance.	Fighter pilots exhibited a higher pressor response to the tilt test compared to transport pilots and nonpilots. Vagal withdrawal and sympathovagal increase induced by the tilt test in fighter pilots were similar to nonpilots but attenuated compared to transport pilots. Greater cardiorespiratory fitness and accumulated flying hours in fighter pilots were associated with lower sympathetic and greater vagal modulation at rest. Specifically, maximal oxygen uptake was strongly correlated with vagal reserve in fighter pilots, and total flying hours were positively correlated with resting HFnu and inversely correlated with resting LFnu and LF/HF.
Albery (2004) Acceleration in other axes affects +Gz tolerance: dynamic centrifuge simulation of agile flight	Observational Study (Cohort Study)	The study involved nine relaxed, unprotected subjects. These participants were exposed to various combinations of lateral (Gy) and transverse (Gx) accelerations in conjunction with +Gz acceleration to assess their tolerance levels.	Subjects were exposed to sustained lateral accelerations of +/- 1, +/- 2 Gy, and transverse chest-to-back accelerations of +1, 2.5, or 4 Gx, or back-to-chest acceleration of -1 Gx. Positive C (+Gz) acceleration was then gradually increased from 1.0 Gz at a rate of 0.1 Gz per second until the subjects experienced near-total vision loss.	The primary outcomes measured were the tolerance levels to +Gz acceleration, heart rate, percent cerebral oxygen saturation, and cerebral blood volumes during each exposure.	The study considered the effects of different combinations of lateral and transverse accelerations on +Gz tolerance. The direction and magnitude of these accelerations were key variables influencing the outcomes.	Adding moderate transverse (+Gx) acceleration significantly reduced +Gz tolerance by approximately 0.25 G when 1.0 or 2.5 Gx was added. Conversely, adding moderate lateral Gy acceleration significantly increased +Gz tolerance by approximately 0.5 G when +2 Gy or -2 Gy was added. The decrease in cerebral blood volume was notably less when +Gz was added to -1 Gx compared to when it was added to +Gx. The study concluded that multi-axis sustained accelerations, such as those experienced during thrust-vectored aircraft maneuvers, can either enhance or reduce the +Gz tolerance of the pilot depending on the direction of the net gravitoinertial force.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Shin, S., & Jee, H. (2019) ACTN-3 Genotype, Body Composition, Fitness, and +Gz Tolerance in Senior Cadets	Observational study (Cross-sectional study)	The study involved 68 senior cadets from the Korea Air Force Academy. The cadets were required to pass a physical fitness test, which included a 3-km run, sit-ups, and push-ups, as well as a body composition test conducted semiannually	The exercise protocol included a physical fitness test and a +Gz test. The +Gz test involved exposure to +6 Gz for 30 seconds. Isokinetic muscle function, including strength and endurance, was also assessed.	The study measured several outcomes, including: • ACTN-3 genotype • Body composition • Physical fitness • Isokinetic muscle function (strength and endurance) • +Gz tolerance.	The study considered the ACTN-3 genotype as a key variable, with cadets showing a dominant fast genetic expression type. The genotype distribution was RR and RX (75%) compared to XX (25%).	No significant difference was found in the effect of the ACTN-3 genotype on +6 Gz test results, body composition, or physical fitness. Body fat percentage and isokinetic muscle strength (peak torque in right leg extension and left leg flexion) were significant predictors of performance in the +Gz test. The study suggests that training focused on RR- and RX-type genotypes could enhance Gz tolerance through improved isokinetic factors like high peak torque and low fatigue index.

AGSM – Anti-G Straining Maneuver; ACTN-3 – Alpha-Actinin-3 (a gene associated with muscle function); ATAGS – Anti-G Training and G Suit; BMI – Body Mass Index; CPT – Cold Pressor Test; CO – Cardiac Output; F-15/16 – Fighter Aircraft Models (F-15 and F-16); G – Gravitational Force; G-LOC – G-induced Loss of Consciousness; Gz – Gravitational Force in the Z-axis (vertical direction); +Gz – Positive Gravitational Force in the Z-axis (e.g., head-to-feet direction); HR – Heart Rate; HRV – Heart Rate Variability; LF/HF – Low Frequency/High Frequency ratio (used in heart rate variability analysis); LIFT – Lead-In Fighter Training; MAP – Mean Arterial Pressure; pNN50 – Percentage of Successive R-R Intervals Differing by More than 50 ms (a measure of heart rate variability); RGT – Relaxed G Tolerance; SGT – Straining G Tolerance; SDNN – Standard Deviation of Normal-to-Normal Intervals (a measure of heart rate variability); TGR – Target G-Force Response; VO_2max – Maximal Oxygen Uptake; IAF – Israeli Air Force

Appendix S6. Details of studies and information relevant to Physiological Effects to G-Tolerance

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Covertino (1998) High sustained +Gz acceleration: physiological adaptation to high-G tolerance	Observational Study (Cohort Study)	The study focuses on high-performance aircraft pilots and other subjects like humans, rats, guinea pigs, and dogs who are exposed to high-G environments. These populations are relevant because they experience significant physiological stress during high-G maneuvers, making them ideal for studying cardiovascular adaptations.	The research involves regular training at high G levels, which is referred to as "G training." This protocol is designed to enhance G tolerance by repeatedly exposing subjects to high sustained +Gz acceleration. The training aims to induce physiological adaptations that improve blood pressure regulation and cerebral perfusion during high-G conditions.	The primary outcomes measured include improvements in blood pressure regulation and protection of cerebral perfusion. These outcomes are crucial for maintaining consciousness and performance during high-G maneuvers. The study also examines the effects of G-layoff, which can lead to reduced G endurance.	The research considers the role of protective technology such as G-suits and anti-G straining maneuvers, which are consistently applied during training. These technologies are essential for mitigating the acute effects of high-G acceleration and are part of the contextual variables that influence the study's outcomes.	The study finds that repeated exposure to high sustained +Gz acceleration leads to significant physiological adaptations. These adaptations are associated with improved blood pressure regulation and enhanced protection of cerebral perfusion during orthostatic challenges. The research supports the notion that regular G training can enhance G tolerance and performance in high-G environment.
Noddeland et al., 1986 Proteinuria in fighter pilots after high +gz exposure	Observational study (Cross-Sectional)	The study involved two groups of fighter pilots. The first group consisted of 20 pilots who participated in +Gz tolerance studies without anti-G suits. The second group included 19 pilots who underwent air combat maneuver training with anti-G suits.	For the first group, the exercise protocol involved exposure to alternating gravitational forces of 3.5 and 5.5 G in a centrifuge. The mean time spent in the centrifuge was 15 minutes. The second group underwent air combat maneuver training, which is a practical exercise involving high G-forces, but with the use of anti-G suits to mitigate the effects.	The primary outcome measured was the presence of proteinuria, which is the presence of excess proteins in the urine. Additionally, the presence of hyaline casts in the urine was also noted.	The use of anti-G suits was a significant variable. The first group did not use anti-G suits, while the second group did. This difference was crucial in understanding the impact of anti-G suits on renal function during high G-force exposure.	In the first group, 17 out of 20 pilots exhibited significant proteinuria and the presence of hyaline casts after centrifugation, indicating a severely depressed renal blood flow during high G-force exposure without anti-G suits. In contrast, none of the pilots in the second group, who wore anti-G suits during their training, showed signs of proteinuria. This suggests that anti-G suits effectively protect against renal strain during high G-force exposure.
Jeon et al., 2013 The effect of exposure to hypergravity on serum biochemical and hematological parameters in jet fighter pilots	Observational Study (Cohort Study)	The study involved eighteen highly-trained, experienced jet fighter pilots. Their ranks were first lieutenant or captain, with a median age of 29 years. All participants were healthy, without cardiovascular issues, and not on any medication.	The pilots were exposed to +9Gz on a human centrifuge, which simulates the high G-forces experienced in jet fighter aircraft. The centrifuge tests were conducted at the Aerospace Medical Training Center, Republic of Korea Air Force. The centrifuge had a rapid onset of 1 G/s, reaching a peak force of +9Gz sustained for 30 seconds.	The study measured serum biochemical and hematological parameters. Blood samples were taken before and immediately after centrifugation to analyze changes in total protein, white blood cell (WBC) count, red blood cell (RBC) count, hemoglobin (Hgb), hematocrit (Hct), and platelet count.	The study was conducted under controlled conditions with a computer-controlled human centrifuge. The pilots performed anti-G straining maneuvers (AGSM) to enhance their tolerance to +Gz, which involves isometric muscle contractions.	Significant increases were observed in total protein (5.0%), WBC count (34.2%), RBC count (3.8%), Hgb (2.0%), Hct (4.3%), and platelet count (7.3%) after +Gz exposure. These changes suggest hemoconcentration, likely due to intense muscular exertion during AGSM. Despite these increases, the post-run values remained within the normal range, indicating that while significant, the changes were not pathological. The study highlights the physiological stress and potential hemoconcentration effects of high +Gz exposure, emphasizing the importance of monitoring these parameters in pilots.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Guillaume et al., 2002 Physiological implications of mechanical effects of plus Gz accelerations on brain structures	Observational Study (Cohort Study)	The study focuses on fighter pilots who are exposed to high +Gz accelerations during certain flight configurations. These conditions can lead to inflight loss of consciousness (G-LOC) due to the rapid and high amplitude of acceleration forces.	The research involved an "in vitro" experiment to measure brain deformations during centrifugation. This setup was used to simulate the mechanical effects of +Gz accelerations on cerebral structures	The study aimed to estimate the stresses imposed on cerebral tissue when the brain is exposed to +Gz acceleration forces. Specifically, it looked at traction, shear, and compression stresses within the brain	The study considered the rapid onset rate and high amplitude of +Gz accelerations as critical factors that could lead to G-LOC. These variables are essential in understanding the mechanical effects on brain structures	The computations from the finite element model indicated that: Traction and shear stresses are enhanced around the tentorial notch. Compression stresses increase at the base of the cerebral hemispheres. Although the amplitude of these stresses is not sufficient to directly disturb proper nerve cell functioning, they could interfere with brain vessels. This interference might enhance vessel collapse and lead to brain ischemia, potentially contributing to G-LOC.
Siitonen et al., 2003 Cerebral blood flow during acceleration in flight measured with SPECT	Observational Study (Cross-sectional Study)	The study involved eight male members of the Finnish Air Force. These participants were selected to evaluate the effects of different G-protection methods during high acceleration in flight	The participants were subjected to two different conditions during flight in the back seat of a BAe Hawk Mk 51 jet trainer at +6 Gz: First, they used the anti-G straining maneuver (AGSM). Second, they used positive pressure breathing for G-protection (PBG) at 24 mmHg.	The primary outcome measured was regional cerebral blood flow (rCBF). This was assessed by injecting a radiotracer, (99m) Tc-ECD, during the +6 Gz flight and scanning the subjects later using single photon emission computed tomography (SPECT).	The study was conducted in two settings: a laboratory setting at +1 Gz and during actual flight conditions at +6 Gz. This allowed for a comparison of cerebral blood flow under different G-force conditions.	The study found that regional cerebral blood flow was reduced by 30% from baseline levels in both conditions (AGSM and PBG). Importantly, PBG was able to maintain cerebral blood flow at +6 Gz without requiring the fatiguing AGSM, suggesting that PBG could be a more sustainable method for G-protection in pilots.
Oliveira-Silva & Boullosa, 2015 Physical Fitness and Dehydration Influences on the Cardiac Autonomic Control of Fighter Pilots	Observational Study (Cross-sectional study)	The study involved 11 healthy male fighter pilots from the Brazilian Air Force. Their average age was 33.2 years, with a body mass of 76.0 kg, height of 1.75 m, BMI of 24.8 kg/m^2, and body fatness of 16.9%. All participants had over 500 hours of flight experience and a minimum of 5 years flying high-performance aircraft. They were free of metabolic and cardiovascular diseases and did not take any medication during the study.	The study included evaluations of body composition, muscular strength, and aerobic capacity. Muscular strength was assessed using resistance exercises like bench press and leg press. Aerobic capacity was measured through a running test on a 400-m track, with speed increments every 2 minutes until exhaustion. Heart rate variability (HRV) was recorded during a control day and a training flight day.	The primary outcomes measured were heart rate (HR) and heart rate variability (HRV) parameters, including RMSSD and sample entropy (SampEn). Dehydration levels were assessed by changes in hematocrit before and after the flight.	The study considered factors such as aerobic capacity, body fatness, and hydration status. The environmental conditions during the study were controlled, with temperatures ranging from 14 to 25°C and relative humidity around 45%.	The flight induced significant reductions in HRV parameters, indicating vagal withdrawal during and after the flight. SampEn during the flight was correlated with aerobic capacity and body fatness. Dehydration was associated with changes in HRV, suggesting that greater dehydration led to reduced vagal modulation. No significant relationship was found between muscular strength and changes in HRV. The study highlights the importance of monitoring aerobic capacity, body fatness, and hydration status to enhance pilots' tolerance to flight stresses.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Assa et al., 2011 Echocardiographic Evaluation and Follow-Up of Cardiac and Aortic Indexes in Aviators Exposed to Acceleration Forces	Observational Study (Cohort Study)	The study involved 96 military jet fighter pilots from the Israeli Air Force (IAF). All participants were male Caucasian aviators who flew high-performance jet aircraft capable of performing up to 9 G. The average age at the initial echocardiographic examination was 19.2 years, and all subjects were healthy without cardiovascular risk factors	The pilots were exposed to high +Gz forces during their flying missions. The cohort was divided into two groups based on their exposure to high G forces: one group with air-to-air missions experiencing approximately 8 minutes of high-G per flying hour, and another group with non-air-to-air missions experiencing about 4 minutes per hour.	Echocardiographic parameters were measured, including left ventricular diameter, interventricular septal thickness, aortic root diameter, and left ventricular mass. The study also monitored for the development of adverse events and changes in cardiac parameters over a follow-up period of 7 to 12 years.	The study considered the variability in "G dose" exposure and its potential impact on cardiac parameters. The echocardiographic examinations were performed using standardized methods and devices, ensuring high reliability in measurements.	No significant changes were observed in cardiac and aortic morphology after long-term exposure to acceleration forces. There were no adverse clinical outcomes noted during the follow-up period. The study found no significant differences in cardiac parameters between pilots exposed to higher G doses and those with standard exposure. The findings suggest that exposure to acceleration forces does not significantly affect cardiac structure and function, supporting the safety of such exposure in healthy individuals.
Ercan & Gunduz, 2020 The Effects of Acceleration Forces on Cognitive Functions	Observational Study (Cross-sectional Study)	The study focused on pilots, examining how their cognitive functions are affected by acceleration forces, specifically +Gz exposure. The analysis included variables such as age, height, and flight hours to determine their impact on cognitive impairment due to G forces.	Pilots underwent Human Centrifuge Training, which simulates high G-force conditions to study their effects on cognitive functions. Cognitive performance was assessed using Time Wall Psychometric Tests conducted before and after the training.	The primary outcomes measured were Post Training Accuracy (PsAc) and Post-Training Mean Arterial Pressure (PsMAP). These outcomes were compared to pre-training values to assess the impact of G forces on cognitive functions	The study considered several contextual variables, including: Age: Younger pilots showed higher PsAc values compared to older pilots. Flight Hours: Pilots with fewer flight hours had lower PsMAP values post-training. Height: Taller pilots showed more significant changes in PsAc values, although height was found to have a small contribution to G tolerance	Cognitive functions were less affected in older and more experienced pilots, suggesting that experience and age contribute to better adaptation to G forces. Cardiovascular changes, particularly in blood pressure, were identified as a primary factor in cognitive dysfunctions caused by +Gz exposure. The study concluded that increased recognition and coping strategies for acceleration forces improve pilots' adaptation over time
Yang et al., 2021 Real-time assessment of global and regional lung ventilation in the anti-gravity straining maneuver using electrical impedance tomography	Observational Study (Cohort Study)	Subjects: 16 healthy male volunteers majoring in aerospace medicine, including 8 undergraduates and 8 teachers. Age: Not explicitly mentioned, but participants were undergraduates and teachers, likely in a typical age range for these categories. Screening: All subjects underwent medical screening and pulmonary function tests to confirm normal lung function.	Training: Subjects reviewed and practiced the Anti-Gravity Straining Maneuver (AGSM) technique with an experienced professor. Setup: Participants were equipped with anti-G suits, helmets, and masks, simulating a real flight cockpit environment. Measurement: Electrical Impedance Tomography (EIT) was used during the AGSM to assess global and regional lung ventilation. Participants performed AGSM in a +1.0 Gz environment.	Global Ventilation: Assessed by measuring the relative depth of gas exchange, duration of gas exchange, duration of exhalation against closed glottis, leakage during exhalation, and stability during AGSM. Regional Ventilation: Ventral and right lung fractions were measured during AGSM. Rating Scores: Subjective ratings of AGSM performance by both the professor and students, compared with and without EIT visualization	Environmental: The study was conducted in a +1.0 Gz environment, simulating conditions similar to those experienced during actual flights. Physical Equipment: Anti-G suits, helmet, and mask were used to simulate flight conditions. Additional Factors: Subjects practiced AGSM repeatedly before being assessed. They also rated their performance based on both subjective experience and real-time EIT data.	Global Ventilation: Teachers showed better performance in terms of relative depth of gas exchange and stability compared to students. No significant difference in leakage during exhalation. Regional Ventilation: Significant differences were found in the ventral fraction of ventilation between teachers and students, with teachers showing better performance. Rating Scores: The ratings of AGSM performance were significantly lower when using EIT compared to subjective ratings, indicating that EIT provided more detailed and objective insights into AGSM performance. EIT as a Tool: EIT demonstrated the ability to objectively assess AGSM performance and could potentially improve training and effectiveness during ground training.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Tsai et al., 2009 Ocular responses and visual performance after high-acceleration force exposure.	Observational Study (Cross-Sectional Study	The study involved 15 men with a mean age of 21.1 years. Participants were screened to exclude those with a history of ocular or systemic diseases such as hypertension, diabetes, glaucoma, cataract, or uveitis.	The participants were subjected to high-acceleration force using a human centrifuge, which applied nine times the gravitational force (ꝛ9 Gz) in the head-to-toe direction. The centrifuge was accelerated to 9 G and held constant for 15 seconds to simulate high G-force conditions.	The study measured visual performance using the ET-DRS visual chart and contrast sensitivity (CS) before and after centrifugation. Ocular responses were assessed through biomicroscopy and corneal topography, focusing on parameters like central corneal thickness (CCT), anterior chamber depth (ACD), and pupillary diameter (PD).	The study was conducted at the Air Force Health Examination and Physiological Training Center in Taiwan. All subjects had remained at sea level for the previous month to ensure consistent baseline conditions.	There was a transient reduction in visual acuity immediately after exposure to high G-force, which returned to baseline within 15 minutes. Significant increases in CCT, ACD, and PD were observed immediately after centrifugation. While CCT returned to baseline within 15 minutes, ACD and PD changes persisted longer. Contrast sensitivity decreased significantly at low and medium spatial frequencies and did not return to baseline within 30 minutes after exposure. The study suggests that high-acceleration forces can induce temporary changes in ocular structures and visual performance, with potential implications for individuals in high-speed environments like aviation or space missions.
Kurihara et al., 2007 Frontal cortical oxygenation changes during gravity-induced loss of consciousness in humans: a near-infrared spatially resolved spectroscopic Study	Observational Study (Cohort Study)	The study focuses on human subjects, specifically targeting pilots who are at risk of experiencing gravity-induced loss of consciousness (G-LOC) due to their exposure to high gravitational forces during flight maneuvers.	The paper does not provide specific details about an exercise protocol. Instead, it examines the physiological responses, particularly cerebral blood flow and oxygenation, under conditions that simulate high gravitational forces, which are relevant to pilots.	The primary outcome measured in this study is the change in frontal cortical oxygenation. This is assessed using near-infrared spatially resolved spectroscopy, a technique that allows for the monitoring of oxygen levels in the brain during G-LOC events.	The main contextual variable in this study is the gravitational force experienced by the subjects. The study investigates how these forces impact cerebral blood flow and oxygenation, which are critical factors in understanding G-LOC.	The study suggests that G-LOC is primarily caused by a reduction in cerebral blood flow, leading to decreased oxygen supply to the brain. This finding highlights the importance of monitoring and managing cerebral oxygenation in pilots to prevent G-LOC during high-G Maneuvers.
Eiken et al., 2017 Intraocular pressure and cerebral oxygenation during prolonged headward Acceleration	Observational Study (Cohort Study)	The study involved two groups of subjects exposed to different levels of gravitoinertial load (+Gz). One group consisted of 10 subjects exposed to 2 and 3 G, while the other group had 12 subjects exposed to 4 and 5 G.	Subjects were exposed to 4-minute plateaus of +Gz at the specified levels (2, 3, 4, and 5 G). This protocol was designed to simulate prolonged headward acceleration and assess its effects on intraocular pressure (IOP) and cerebral oxygenation.	The primary outcomes measured were: • Intraocular Pressure (IOP) at 1, 2, and 3 G levels. • Mean Arterial Pressure (MAP) at eye level. • Oxygenation of the cerebral frontal cortex	The study considered the effects of prolonged exposure to moderately elevated +Gz on IOP and cerebral anoxia reserve. The risk of unconsciousness was noted to be higher when anti-G-garment failure occurred after prolonged exposure	IOP remained consistent across 1, 2, and 3 G levels, indicating that Gz loading did not affect IOP (14.1 ± 1.6 mmHg at 1 G, 14.0 ± 1.6 mmHg at 2 and 3 G). MAP showed an initial drop followed by partial recovery, with end-exposure values reduced by up to 30 mmHg. Cerebral oxygenation experienced an initial drop without recovery, leading to a plateau or further slight decrement, reaching a minimum of about −14 μM. The study suggests that the increased risk of unconsciousness upon G-garment failure after prolonged +Gz exposure is due to a reduced cerebral anoxia reserve, as cerebral oxygenation remained suppressed despite partial recovery of MAP.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Ozturk et al., 2012 Cardiac responses to long duration and high magnitude +Gz exposure in pilots: an observational study	Observational Study (Cohort Study)	The study involved 63 pilots who applied for aircrew periodic medical examination. Participants were divided into two groups: 33 high-performance aircraft pilots (Group A) and 30 transport/helicopter pilots (Group B).	The study did not involve an exercise protocol. Instead, it was an observational study focusing on the effects of occupational exposure to +Gz acceleration on pilots.	The study evaluated 21 echocardiographic parameters to assess cardiac responses. Key parameters included tricuspid valve peak velocity during late diastolic filling (TV A) and the ratio of peak velocity during early diastolic filling to late diastolic filling (TV E/A).	The primary contextual variable was the type of aircraft flown by the pilots, which determined their exposure to +Gz forces. The study compared high-performance aircraft pilots with transport/helicopter pilots to assess the impact of different +Gz exposure levels	The study found that long-term +Gz exposure did not affect cardiac morphologic and systolic functions. However, it did have effects on right ventricular diastolic functions, as evidenced by the significantly higher mean TV A and lower TV E/A ratio in Group A pilots. These changes may be due to chronic adaptation to +Gz forces or elevated pulmonary artery pressure (PAP) levels
Gillingham, 1988 High-G stress and orientational stress: physiologic effects of aerial maneuvering	Observational Study (Cohort Study)	The study focuses on pilots of modern fighter aircraft who are susceptible to high-G stress, which can lead to G-induced loss of consciousness (GLC).	The paper discusses physiological means to increase G tolerance, which include frequent exposure to G stress and physical conditioning such as weight training and moderate aerobic Conditioning.	The primary outcomes measured are the symptoms of visual loss and GLC due to high-G stress. These symptoms are linked to decreased head-level blood pressure and cardiac output.	The study considers the body's natural defenses against G stress, such as neural tissue energy reserves and cardiovascular baroceptor reflexes, which influence the G-time tolerance curve.	The research identifies three main categories for raising G tolerance: mechanical, physiological, and educational methods. Mechanical methods include anti-G suits and special seating arrangements. Educational methods involve high-G training and briefings. An improved anti-G valve, physical conditioning, high-G awareness briefings, and centrifuge training are currently being applied to prevent GLC in fighter aircraft pilots. Future aircraft may require advanced measures like assisted positive-pressure breathing (APPB), pilot selection, and high-G seats to protect pilots from sustained high G forces.

AGSM - Anti-G Straining Maneuver; BAe - British Aerospace; CCT - Central Corneal Thickness; G-LOC - G-induced Loss of Consciousness; Gz - Gravitational Force in the z-axis; HR - Heart Rate; HRV - Heart Rate Variability; IOP - Intraocular Pressure; MAP - Mean Arterial Pressure; PBG - Positive Pressure Breathing; PsAc - Post-Training Accuracy; PsMAP - Post-Training Mean Arterial Pressure; PVC - Premature Ventricular Contractions; RMSSD - Root Mean Square of Successive Differences; SampEn - Sample Entropy; TV A - Tricuspid Valve Peak Velocity (Late Diastolic Filling); TV E/A - Ratio of Peak Velocity During Early to Late Diastolic Filling; WBC - White Blood Cell Count; RBC - Red Blood Cell Count; Hgb – Hemoglobin; Hct – Hematocrit; EIT - Electrical Impedance Tomography; SPECT - Single Photon Emission Computed Tomography

Appendix S7. Details of studies and information relevant to Training and Prevention to Increase G Tolerance

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Lyons et al., 1997 Assessment of the anti-G straining maneuver (AGSM) skill performance and reinforcement program	Observational Study (Cohort Study)	The study involved USAF fast jet pilots, specifically those assigned to the United States Air Forces Europe (USAFE). A total of 78 surveys were completed out of 110 distributed, indicating a response rate of 71%. The pilots surveyed included those flying F-16, F-15C, and F-15E aircraft	The program involved recording head-up display videotapes (HUD tapes) during flights. These tapes were critiqued during debriefings by flight leads to assess the AGSM technique and continuity. The focus was on reinforcing the proper performance of the anti-G straining maneuver (AGSM) in flight.	The study measured deficiencies in AGSM performance, such as timing of breathing, inhalation duration, and the ability to “get the jump on the Gs.” It also assessed the frequency of talking during +Gz exposures and the effectiveness of the program in correcting these deficiencies.	The study was conducted in the context of ongoing efforts since the mid-1980s to enhance pilot awareness of G-induced loss of consciousness (G-LOC) through briefings, videotapes, and safety articles. The program was initiated in response to aircraft accidents caused by improperly performed AGSMs.	A significant number of pilots (73%) reported one or more problems with their AGSM. The most common issue was the timing of breathing being too quick, reported by 33 pilots. The program was successful in correcting 64% of the reported deficiencies, with the highest success in remediating timing problems (91% correction rate for quick breathing timing). Other issues, such as inhalation duration and talking during +Gz exposures, were also addressed, though with varying success rates.
Plioutsias & Karanikas, 2015 Using STPA in the evaluation of fighter pilots training programs	Conference paper	Subjects: Fighter pilots operating F-16 aircraft from a South European Air Force (SEAF). Demographics: Specific demographics not fully detailed, but the study is based on a South European Air Force’s fighter pilot population.	Training Program: The focus is on an Air Combat Maneuvers (ACM) mission scenario, with pilots trained in a simulated multi-tasking environment involving high-G maneuvers, threats from hostile aircraft, and maintaining aircraft formation	Safety Constraints: Assessment of adherence to safety constraints such as maintaining a minimum distance, avoiding excessive G loads, and executing the Anti-G Straining Maneuver (AGSM) when exceeding 2 Gs. Control Actions: Actions such as maintaining separation between aircraft and controlling G forces during high-performance maneuvers. Feedback Mechanisms: Measurement of the effectiveness of various feedback systems, including HUD (Head-Up Display) indicators, audio warnings, and visual cues to alert pilots of potential issues or violations of safety constraints.	Aircraft and Mission: Focus on F-16 fighter aircraft and Air Combat Maneuvers (ACM) missions with two aircraft formations. Safety Constraints (SC): Different SCs were monitored, such as maintaining minimum altitude, adhering to fuel levels, and performing AGSM during high-G maneuvers. Feedback Mechanisms: The use of visual and auditory alerts through the HUD, aircraft radar, and other instruments to inform pilots about potential safety breaches.	Inadequate Coverage in Training: The study found that the existing flight training program did not sufficiently cover scenarios involving multiple safety constraint violations or the consequences of such violations. Single Sense Dependence: Some safety constraints relied on only one sense (e.g., vision), increasing the risk of misinterpretation or failure when pilots’ senses were impaired. Workload and Feedback Overload: Multiple safety constraint violations could overwhelm pilots with excessive feedback, leading to potential performance degradation and decision delays, especially if the HUD fails. Improvement Recommendations: The study recommended including more complex training scenarios involving multiple SC violations, improving feedback mechanisms to involve multiple senses, and enhancing the aircraft systems to better support pilots in high-stress situations.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Sah, Nataraja, & Rastogi, 2018 Quantified Muscular Contraction during AGSM and its Correlation with Straining +Gz Tolerance	Observational Study (Cross-Sectional Study)	Subjects: 25 healthy male ab-initio fighter aircrew members, aged between 21 to 30 years. Selection: Participants were selected from the Indian Air Force (IAF) and were free from any disease or disability at the time of the study.	Training Protocol: The participants underwent a formal AGSM (Anti-G Straining Manoeuvre) training program. The training involved practicing the AGSM technique using the High Performance Human Centrifuge (HPHC). Electromyographic (EMG) recordings were taken from four muscle groups involved in AGSM (upper torso: pectoralis major, lower torso: rectus abdominis, thigh: vastus lateralis, and calf: gastrocnemius) to assess muscle activity. The training also included Gradual Onset Run (GOR) to assess relaxed and straining G tolerances pre- and post-training.	G Tolerance: Measured pre- and post-training for both relaxed and straining G tolerances. Straining G tolerance showed an improvement after training. EMG Activity: Measured the muscular contraction during AGSM using surface EMG (SEMG) for the muscle groups involved. The activity of thigh and calf muscles was specifically correlated with increased straining G tolerance.	Instrumentation: Surface EMG (SEMG) was used to record muscle activity. The HPHC was used for G tolerance testing under centrifuge conditions. Training Setup: Pre- and post-training data collection involved two centrifuge sessions (one before and one after the training).	Increase in G Tolerance: Post-training straining G tolerance increased from 5.69G (pre-training) to 6.13G (post-training). There was no significant change in relaxed G tolerance. Muscle Activity: Significant increase in EMG values for all muscle groups after training. Thigh muscles showed the highest correlation with post-training straining G tolerance ($r = 0.343$), followed by calf muscles ($r = 0.212$). EMG data indicated that lower limb muscles (thigh and calf) played a more significant role in AGSM performance compared to trunk muscles (chest and abdomen).
Geng, Wang, Yan, Chu, & Zhan, 1999 Two high performance fighter pilots with low +Gz tolerance rectified by centrifuge training	Observational Study (Case-Study)	Subjects: Two high-performance fighter aircraft pilots. Demographics: The study specifically focuses on pilots with low +Gz tolerance. Selection: Pilots selected for this study had previously exhibited low tolerance to +Gz acceleration forces.	Training Protocol: The pilots underwent Anti-G Straining Maneuver (AGSM) and Pressure Breathing for +Gz (PBG) maneuvers during centrifuge +Gz stress training. The training aimed to enhance their ability to tolerate higher levels of G-force by improving their AGSM and PBG skills, combined with the use of an anti-G suit to assist in counteracting the effects of G-forces during high-acceleration maneuvers.	+Gz Tolerance: +Gz tolerance with AGSM: After training, the +Gz tolerance with AGSM was enhanced by 3.0 ~ 3.25 G. +Gz tolerance with PBG and anti-G suit: After training, the +Gz tolerance with PBG and the anti-G suit was enhanced by 2.75 ~ 3.0 G. The combined +Gz tolerance (with both AGSM, PBG, and anti-G suit) was higher than the relaxed +Gz tolerance by 4.25 ~ 4.5 G. SACM +Gz Profile: Both pilots successfully passed the 8 G 10 s SACM +Gz profile and reached the training standard.	Training Environment: Centrifuge was used for training under controlled +Gz stress conditions. Equipment: Pilots wore anti-G suits and practiced both AGSM and PBG maneuvers. Stress Profile: The 8 G 10 s SACM profile was a key measure of success, testing the pilots' ability to endure high +Gz forces.	Increased G-Tolerance: Training with AGSM, PBG, and anti-G suit led to significant improvements in the pilots' +Gz tolerance. The combined +Gz tolerance after training was 4.25 ~ 4.5 G higher than their relaxed G tolerance. Successful Completion: Both pilots successfully passed the 8 G 10 s SACM +Gz profile, meeting the training standard and demonstrating the effectiveness of the training program.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Rausch et al., 2021 The effects of 12 weeks of functional strength training on muscle strength, volume and activity upon exposure to elevated Gz forces in high-performance aircraft personnel	RCT (Randomized Controlled Trial)	The study involved 18 participants, including 3 active jet pilots and 15 novice pilots with little to no experience with G-forces. The training group consisted of 12 participants (including one female), while the control group had 6 participants (including one female).	Participants in the training group underwent a 12-week functional strength training program. This program included whole-body strength routines focusing on the neck, abdominal, and shoulder muscles. The training was designed to be portable, requiring no special equipment, and could be performed anywhere.	The study measured the volume and strength of neck and shoulder muscles using MRI and specialized strength apparatus. It also assessed muscle activity and strain during exposure to elevated G-forces in a centrifuge. The perception of muscle strain was evaluated using a five-point scale.	The study was conducted in a controlled environment using a long-arm centrifuge to simulate flight-specific hypergravity conditions. Participants were exposed to G-forces ranging from +1.4 to +3 Gz under different conditions, including wearing a helmet and night vision goggles.	The training group showed significant increases in muscle strength and volume compared to the control group. The maximal isometric strength increased in all exercises for the training group, while the control group showed no significant changes. Muscle activity, as measured by electromyography, decreased in the training group when wearing a helmet, indicating improved efficiency. The control group showed higher muscle activity when wearing a helmet and night vision goggles compared to the training group. Despite these improvements, the perceived muscle strain did not significantly differ between the groups, although there was a trend towards reduced strain in the training group. The study concluded that functional strength training enhances muscle strength and volume, reduces muscle activation under G-forces, and potentially reduces fatigue during prolonged exposure to elevated G-forces.
Smith, 2017 Comparative Analysis of the USAF F-16 and RAAF F-18 Training Programs	Comparative multi-case study	The research involved current USAF F-16 and RAAF F-18 pilots, as well as exchange pilots who had experienced both training programs. The participants' experience in various fighter aircraft, including flight hours and qualifications, provided insights into the differences and similarities of the training programs .	Both the USAF and RAAF training programs consist of a six-month course, structured around academic, simulator, and flight training phases. These include: • Conversion Phase: Focuses on basic aircraft handling, takeoff, landing, and emergency procedures. • Air-to-Air Phase: Involves basic dogfighting and progressively more complex combat scenarios. • Air-to-Surface Phase: Covers precision and non-precision air-to-ground weaponry and large force exercises.	The primary outcome measured was the efficacy of the training programs in producing mission-ready fighter pilots. Feedback on various instructional approaches, the balance of training elements (academic, simulator, and flight), and the overall effectiveness of the training methods were key factors evaluated.	Significant contextual variables include cultural differences between the USAF and RAAF training environments, the availability of resources, and technological advancements. These factors influenced how training was structured, the stress levels applied, and how each program adjusted based on student needs and available resources.	Similarities: Both programs have similar structures, including the training sequence (academic, simulator, flight) and duration. The ultimate goal in both is to produce proficient wingman pilots ready for operational deployment . Differences: Cultural distinctions between the USAF and RAAF were notable. The USAF's training is more standardized across squadrons, whereas the RAAF, with its smaller scale, allows more flexibility and faster adjustments. The USAF also has a larger pool of resources, while the RAAF maintains stricter standards, often resulting in a higher failure rate in their program . These findings and the outlined training protocols offer valuable insights for improving fighter pilot training policies across both forces.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Slungaard et al., 2018 Content Validity of Level Two of the Royal Air Force Aircrew Conditioning Programme	Descriptive study	The study focuses on Royal Air Force (RAF) aircrew, with a specific emphasis on UK fast-jet aircrew. The prevalence of flight-related neck pain is notably high, affecting 66% of all RAF aircrew and 70% of UK fast-jet aircrew.	The RAF Aircrew Conditioning Programme (ACP) is designed to enhance pilot performance by reducing fatigue and strain injuries, particularly targeting the neck. Level two of the ACP is delivered to student aircrew who have completed basic instruction in cervical spine stability, core stability, and initial technique instruction for strength training. The program includes an overall exercise approach with 5 items and specific exercise sessions comprising 24 items, evaluated for relevance and simplicity.	The content validity of the ACP was assessed by six international medical experts. The item-content validity index (I-CVI) was used to measure the proportion of experts rating an item/exercise as acceptable (score 3-4). Protocol-CVI was calculated as the average I-CVI across items, with results showing excellent relevance (0.90) and good simplicity (0.83).	The need for sufficient supervision during exercises was highlighted to ensure safe execution and maintain adherence. The complexity of neck exercises necessitates additional supervision to enhance simplicity and effectiveness.	The ACP demonstrated excellent content validity for relevance to the target population. While the program is well-suited for its intended audience, the complexity of certain exercises requires careful supervision to ensure safety and adherence. The study underscores the importance of tailored exercise programs in reducing neck pain and improving performance among aircrew.
Gillingham & Fosdick, 1988 High-G training for fighter aircrew.	Observational Study (Cohort Study)	The study involved 744 USAF fighter aircrew who underwent high-G training at the USAF School of Aerospace Medicine. The training was conducted from January 1985 to February 1986. The participants were from various laboratories, including the Tactical Air Command.	The high-G training course was completed in one day and included a 2-hour lecture, a series of centrifuge rides, and a short debriefing. Trainees were subjected to five standard training G profiles on the centrifuge, with the option to experience an additional one. The training focused on performing an effective anti-G straining maneuver (AGSM) to increase G tolerance.	The primary outcome measured was the increase in G tolerance resulting from improved skill in performing an AGSM. Secondary outcomes included a better understanding of the physiological mechanisms of G stress and G tolerance, increased respect for the hazards associated with high-G environments, and enhanced confidence in tolerating high-G stress.	The training emphasized the significance of the G-time tolerance curve and the importance of understanding the physiological mechanisms that protect against G stress. The course also covered mechanical and physiological methods of G protection, such as the use of anti-G suits and physical Conditioning.	The mean relaxed and straining G tolerances on the gradual-onset run (GOR) without anti-G suit inflation were 5.2 and 8.3 G, respectively. 41% of the trainees reached the 9.0-G run limit. G-induced loss of consciousness (G-LOC) occurred in 9% of the trainees, most commonly on the GOR. The training was well-received, with 73% of the trainees providing enthusiastic or positive assessments.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Sekiguchi et al., 1986 Anti-G training of Japanese Air Self Defense Force fighter pilots.	Observational Study (Cohort Study)	The study involved 138 fighter pilots from the Japanese Air Self Defense Force. These pilots were divided into two groups: 62 F-15 trainees and 76 F-4 trainees	Day 1 included a physical examination and a briefing on high-G stress and protective methods. From days 2 to 5, pilots underwent centrifuge rides in two basic patterns: tracking performance and simulated aerial combat maneuver (SACM). Day 6 involved debriefing and completing questionnaires.	G tolerance was measured in two scenarios: gradual onset run (GOR) and rapid onset run (ROR). GOR relaxed tolerance was +5.5 ± 0.7 Gz, while ROR relaxed tolerance was +4.9 ± 0.6 Gz. Incidents of loss of consciousness (LOC) were recorded, with 18 F-15 trainees and 15 F-4 trainees experiencing LOC during basic patterns. Arrhythmias were also monitored, with more than half of the trainees developing various types, including premature ventricular contractions (PVC), supraventricular premature contractions (SVPC), A-V dissociation, S-A block, and atrial fibrillation (AF)	The difference in G tolerance between F-15 and F-4 trainees was not significant in either GOR or ROR. One case of atrial fibrillation developed Wolff-Parkinson-White (WPW) syndrome and atrial fibrillation, followed by LOC during a 4-G warm-up pattern.	All F-15 trainees met the training goal and completed the SACM pattern on day 5 without experiencing LOC. The study highlights the physiological challenges faced by pilots due to the high G-producing capabilities of modern fighter aircraft, which exceed human physiological G tolerance. The training program was effective in preparing pilots to handle high sustained +Gz (HSG) conditions, despite the occurrence of LOC and arrhythmias in some trainees.
Cammarota & Whinnery, 1990 Enhancing aircrew centrifuge high-G training using on-line videotape documentation	Observational Study (Pre-post Design)	The study focuses on fighter aircrew, specifically Navy and Marine aviators, who are undergoing high-G training. These individuals are trained to improve their tolerance to high-G environments, which are common in fighter aircraft operations.	The training involves the use of human centrifuges, which simulate the high-G forces experienced during flight. The protocol includes continuous monitoring and documentation of various physiological parameters during the centrifuge session.	Several key outcomes are measured during the training: Continuous electrocardiographic (ECG) display to monitor heart activity. Anti-G suit pressure tracing to assess the effectiveness of the suit in counteracting G-forces. Heart rate parameters to evaluate cardiovascular response. +Gz parameter, which indicates the level of G-force experienced. Duration of incapacitation if G-induced loss of consciousness (G-LOC) occurs.	The training is conducted at the Naval Air Development Center (NADC), which provides a controlled environment for high-G training. The use of videotape documentation allows for detailed analysis and review of each training session, enhancing the learning experience for the aircrew.	The integration of these techniques and the comprehensive documentation of training sessions have been well received by the participating aviators. The enhanced training methods provide valuable insights into the physiological responses to high-G forces and help improve the aircrew's tolerance and performance in such environment.

ACGSM - Anti-G Straining Maneuver; AF - Atrial Fibrillation; A-V – Atrioventricular; ECG – Electrocardiogram; GOR - Gradual Onset Run; G-LOC - G-induced Loss of Consciousness; Gz - G-force in the z-axis; HPHC - High Performance Human Centrifuge; I-CVI - Item-Content Validity Index; LOC - Loss of Consciousness; PVC - Premature Ventricular Contractions; RAAF - Royal Australian Air Force; ROA - Rapid Onset Run; SACM - Simulated Aerial Combat Maneuver; SEAF - South European Air Force; SVPC - Supraventricular Premature Contractions; USAF - United States Air Force; WPW - Wolff-Parkinson-White syndrome

Appendix S8. Details of studies and information relevant to Physical Training and Conditioning for Pilots

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Newman et al., 1999 Patterns of physical conditioning in royal Australian air force F/A-18 pilots and the implications for plus Gz tolerance	Observational Study (Cohort Study	The study focused on Royal Australian Air Force (RAAF) F/A-18 fighter pilots. A total of 42 pilots participated in the questionnaire survey. A subset of eight pilots underwent aerobic fitness testing using a cycle ergometer.	The pilots reported engaging in regular physical conditioning, with 86% participating in exercise routines. Aerobic activities were predominant, with 83% of pilots engaging in them, and running was the most popular activity (55%). Anaerobic activities were less common, reported by 26% of the respondents. The average weekly training volume was 129 ± 77 minutes.	The primary outcome measured was aerobic fitness, specifically the maximum oxygen uptake (VO$_2$maxVO$_2$max). The mean VO2maxVO2max for the pilots was 50 ± 6 ml O22·kg^{-1}−1·min−1^{-1}.	The study considered the high +Gz environment in which fighter pilots operate, which can influence the importance of physical conditioning. The focus was on understanding how different types of physical conditioning might relate to +Gz tolerance.	A high rate of participation in regular physical activity suggests that physical fitness is valued among fighter pilots. Aerobic activities were more common than anaerobic ones, indicating a preference or perceived importance of aerobic conditioning. The measured aerobic fitness levels were good but not exceptionally high, suggesting they might not significantly influence +Gz tolerance. The study highlights the need for further research to determine the optimal balance of aerobic and anaerobic conditioning for enhancing +Gz tolerance.
Erneston et al., 2022 A Preliminary Analysis of the Costs and Benefits of Physical Therapy and Strength Training for Fighter Pilots	Observational Study (Pre-post Design)	The study focuses on high-performance aircraft pilots, commonly referred to as “fighter” pilots. These individuals face unique occupational hazards that can lead to injuries, time lost from flying, and potential career termination.	The paper does not provide specific details about the exercise protocol used in the preventative health program. However, it implies that the program includes physical therapy and strength training as part of its preventative and rehabilitative health solutions.	The primary outcomes measured in the study include: Direct medical costs related to injuries, estimated at approximately $531,000 annually for the pilots covered by the program. Work loss costs, estimated at about $4.7 million annually. Pilot retention improvement rates, which are crucial for determining the program’s cost-effectiveness.	Several variables were considered in the analysis, including: Discount rate: This affects the present value of future costs and benefits. Medical cost avoidance: The potential reduction in medical costs due to the program. Pilot retention improvement rate: The increase in the number of pilots retained due to the program.	The study found that while the program may not completely cover outpatient and work loss costs, even a minor improvement in pilot retention (about 1-3 additional retentions per year) can result in a net positive annual benefit. The equivalent annual worth (EAW) analysis showed that the program’s benefits become positive when pilot retention improvements are factored in, despite the consistently negative EAW when only considering direct medical and work loss costs.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Sovelius et al., 2006 Trampoline exercise vs. strength training to reduce neck strain in fighter pilots	Randomized Controlled Trial (Parallel-group RCT)	The study involved 16 volunteer Finnish Air Force cadets. These participants were divided into two groups: a strength training group (STG) and a trampoline training group (TTG).	Strength Training Group (STG): Participants performed dynamic flexion and extension exercises, along with isometric rotation exercises. Trampoline Training Group (TTG): Participants engaged in trampoline bouncing exercises. The training period lasted for 6 weeks	Muscle strain was recorded using electromyography (EMG) from the sternocleidomastoid, cervical erector spinae, trapezius, and thoracic erector spinae muscles. Measurements were taken during in-flight conditions and cervical loading testing (CLT).	The study was conducted in the context of high demands on muscular strength and endurance faced by fighter pilots. The focus was on reducing muscular loading and preventing injuries due to fatigued muscles.	Both training methods effectively reduced muscle strain during in-flight and CLT, particularly in the cervical muscles. In the STG, muscle strain reductions were observed as follows: sternocleidomastoid (50%), cervical erector spinae (3%), trapezius (4%), and thoracic erector spinae (8%). In the TTG, reductions were: sternocleidomastoid (41%), cervical erector spinae (30%), trapezius (20%), and thoracic erector spinae (6%). After a 3-month follow-up with intensive high +Gz flying, EMG during CLT remained lower than baseline measurements. No statistically significant difference was found between the two training groups, suggesting both methods are beneficial. The study recommends incorporating both strength and trampoline training into fighter pilots' physical education programs to enhance muscle capacity in different ways.
Ferreira et al., 2025 The Feeling of Fatigue Scale for Brazilian Fighter Pilots	Observational Study (Cross-Sectional Study)	The study focused on Brazilian fighter pilots. A total of 58 pilots participated, operating F-5M and JAS 39E aircraft. The study was conducted over a period from March to August 2023.	The study did not involve a physical exercise protocol but rather an assessment protocol. Participants completed a sociodemographic questionnaire, the Feeling of Fatigue Scale (FFS), and the Samn-Perelli Scale. These assessments were conducted at two different times with a maximum interval of 7 days between them.	The primary outcome measured was mental fatigue. The study evaluated the psychometric properties of the FFS, including reliability, reproducibility, and agreement. Criterion validation was performed using the Samn-Perelli Scale.	The study considered variables such as drowsiness, concentration, and physical discomfort. These variables were assessed to determine the reliability of the FFS in measuring mental fatigue.	The FFS demonstrated good reliability for evaluating drowsiness, concentration, and physical discomfort. The reliability scores were: drowsiness (Cronbach's $\alpha = 0.840$), concentration (Cronbach's $\alpha = 0.907$), and physical discomfort (Cronbach's $\alpha = 0.747$). The FFS was found to be valid and accurate for assessing mental fatigue in Brazilian fighter pilots.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Honkanen et al., 2018 Assessment of Muscular Fitness as a Predictor of Flight Duty Limitation	Observational Study (Cohort study)	The study involved two groups of military pilots: 23 pilots with Gz limitations due to spinal disorders. 50 experienced pilots (with over 1,000 flight hours) who were symptomless and actively flying operative missions	The Finnish Air Force used a combination of aerobic and muscular fitness tests during the selection process for military pilot candidates. Aerobic fitness was assessed using a maximal ergometer test. Muscular endurance was evaluated through a battery of five tests: standing long jump, pull-ups, sit-ups, back extensions, and push-ups.	The study measured the results of the physical fitness tests and compared them between pilots with and without Gz limitations. Specific focus was on the pull-up and back extension tests, as well as the total muscular fitness test score.	The study also considered self-reported physical activity levels and participation in competitive sports at the time of pilot selection. Anthropometric measures were recorded, although they did not show significant differences between the groups.	Pilots without Gz limitations had significantly better results in pull-up and back extension tests compared to those with limitations. Non-limited pilots also had a higher total muscular fitness test score and were more likely to have participated in competitive sports. Aerobic fitness and anthropometric measures did not significantly differ between the groups. The findings suggest that higher levels of muscular fitness, particularly axial strength, may protect against spinal disorders that could limit flight duty.
Fernandes et al., 2003 Muscle activity in pilots with and without pressure breathing during acceleration	Observational Study (Cohort Study)	The study involved seven Swedish Air Force fighter pilots who volunteered to participate in the experiment. These pilots were exposed to high acceleration forces in a controlled environment using a human centrifuge.	The pilots underwent two types of runs: gradual and rapid onset runs to +9 Gz. These runs were conducted with and without the use of positive pressure breathing for G protection (PBG).	The primary outcomes measured were mean muscle activity, relative time with high muscle activity levels, and individual activation preferences. Muscle activity was recorded using surface electromyography from various muscle groups, including the intercostals, rectus abdominis, vastus lateralis, biceps femoris, and gastrocnemius lateralis.	The study compared the effects of using PBG versus not using it during high G-force exposure. The focus was on how these conditions affected muscle activity and G duration tolerance.	G duration tolerance was significantly longer when PBG was used, with pilots enduring 57 seconds compared to 32 seconds without PBG during rapid onset runs. The vastus lateralis and gastrocnemius lateralis muscles showed less relative time with high muscle activity when PBG was used (0.3% and 12.7%, respectively) compared to the control condition (5.8% and 33.6%, respectively). The study found that pilots had individual preferences for muscle activation sequences while performing anti-G straining maneuvers (AGSMs), with some preferring to contract leg muscles and others abdominal muscles.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Wiegman et al., 1995 The role of anaerobic power in human tolerance to simulated aerial combat maneuvers	Observational Study (Cohort Study)	The study involved 10 adult males. Specific details about their age range or other demographic characteristics are not provided in the context.	The exercise protocol included Wingate anaerobic tests (WT) to determine upper and lower body anaerobic indices. Acceleration tolerance was measured using a simulated aerial combat maneuver (SACM) centrifuge profile. This involved alternating 4.5 and 7 +Gz 15-second plateaus until exhaustion.	Anaerobic Power: Lower body 30-second mean power (MP) and peak power (PP) were measured, with group means of 620 ± 128 W and 851 ± 169 W, respectively. Upper body MP and PP were also measured, with group means of 380 ± 68 W and 497 ± 81 W, respectively Blood Lactate Levels: Peak blood lactate concentration was recorded at 4.9 ± 1.5 mmol/L. Perceived Exertion: The overall rating of perceived exertion was measured using the Borg Category-Ratio Scale, with a group mean of 7.4 ± 2.1.	Anthropometric Measurements: Various body circumferences, weight, fat-free body weight, and height were considered as contextual variables.	Correlation with SACM Duration: SACM duration time was positively correlated with lower body MP and PP, upper body PP, and various anthropometric measurements such as body circumferences, weight, fat-free body weight, and height. There was no correlation between SACM duration and WT power outputs relative to body weight or other SACM variables. Importance of Anaerobic Power: The study suggests that anaerobic power is a significant physiological component in tolerance to simulated aerial combat maneuvers.
Slungaard et al., 2019 Aircrew Conditioning Programme Impact on +Gz Tolerance	Observational Study (Cohort Study)	The study involved 36 aircrew members from the UK Royal Air Force and Royal Navy. Participants were divided into two groups: 17 individuals participated in the Aircrew Conditioning Programme (ACP), and 19 served as a control group.	The ACP consisted of aerobic and muscle-strengthening exercises. These exercises were performed twice weekly over a 12-week period. The program aimed to improve overall fitness and reduce the risk of injury among aircrew members	The study assessed several markers of G tolerance, including Relaxed G Tolerance (RGT) and Straining G Tolerance (SGT). G endurance was evaluated through repeated simulated air combat maneuvers (SACMs). Physiological variables such as heart rate (HR) and blood pressure (BP) were recorded during centrifuge testing	The study focused on the physiological responses of aircrew members to high +Gz acceleration. The impact of the ACP on these responses was measured before and after the intervention.	The ACP did not negatively affect RGT, as there were no significant changes in RGT, HR, or BP responses. During SGT profiles, a lower HR at a given +Gz level was observed in the exercise group post-ACP, indicating reduced physiological strain. The ACP tended to improve the ability to tolerate repeated Gz exposure, as evidenced by an increased proportion of individuals completing the SACM profiles. Overall, the ACP was beneficial in reducing physiological strain during high +Gz exposure without negatively impacting G tolerance.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Tomczak & Haponik, 2016 Physical fitness and aerobic capacity of Polish military fighter aircraft pilots.	Observational Study (Cross-Sectional Study)	The study focused on 120 Polish military fighter aircraft pilots, all male, with an average age of 37.13 years. The pilots were divided into three age groups: under 29, 30-39, and 40-49, based on the American Heart Association's classification for assessing aerobic capacity.	The physical fitness of the pilots was assessed using a test consisting of seven skill exercises: zigzag pattern run, 10 × 10 m run, pull-ups, push-ups on a bench, a 2-minute session of sit-ups, standing long jump, and a 50 m swim. Aerobic capacity was measured using the Åstrand-Ryhming test on a MONARK cycling ergometer, which involved 5-8 minutes of submaximal exercise with heart rate monitoring.	The study measured physical fitness through the results of the seven skill exercises and aerobic capacity through maximal oxygen consumption (VO_2 max). The average VO_2 max was found to be 33.73 ml/kg/min, indicating a medium level of aerobic capacity.	The study considered age as a significant variable, noting that physical fitness decreases with age. The pilots' body mass index (BMI) was also analyzed, revealing that 65% were overweight and 15% were obese, which could impact their physical performance.	Polish military fighter aircraft pilots have a medium level of physical fitness and aerobic capacity, which is lower than 30 years ago, indicating a negative trend. There are significant differences in physical fitness levels among different age groups, with older pilots generally showing decreased fitness. The study highlights the need for military aviation medicine physicians and physical education specialists to address the declining physical fitness levels among pilots. The study suggests that the physical fitness of Polish pilots is satisfactory compared to other military groups, but their aerobic capacity is lower than that of pilots from other countries, which is a concern for their operational readiness.
Rintala et al., 2015 Relationships Between Physical Fitness, Demands of Flight Duty, and Musculoskeletal Symptoms Among Military Pilots	Observational Study (Cohort Study)	The study involved 195 male Finnish military pilots who were selected based on their participation in compulsory fitness tests over the preceding 6 months. They were divided into three groups: high-G, low-G, and HQ, based on their flight duty profiles. The high-G group consisted of pilots flying high-performance aircraft, the low-G group flew propeller aircraft, and the HQ group held headquarters posts and did not fly actively. The mean age varied across groups, with the high-G group being the youngest.	The pilots' physical fitness was assessed using a series of tests, including a maximal aerobic capacity test on a bicycle ergometer and muscular fitness tests involving sit-ups, push-ups, squats, and an isometric hand grip test. The intensity of physical activity was self-reported in terms of weekly hours spent on endurance and strength exercises.	The study measured the occurrence of flight-induced musculoskeletal symptoms, the degree of resulting disabilities using Visual Analog Scales (VAS), and the prevalence of occupational cervical spine degeneration. The pilots' physical fitness and the intensity of their physical activity were also evaluated.	Variables such as age, body mass index (BMI), tobacco use, flight hours, and their accumulation were considered in the analysis. The study also looked at the relationship between these variables and the degree of disability both on duty and off duty.	The high-G group exhibited the highest aerobic capacity and muscular fitness scores. Despite experiencing more musculoskeletal pain, they reported fewer disabilities, highlighting the importance of physical training for operational readiness. Over 90% of pilots reported flight duty-induced musculoskeletal symptoms, with the high-G group experiencing the most symptoms. However, the fittest pilots suffered fewer disabilities. The study found that the degree of disability was more pronounced off duty than on duty, and the percentage of high-performance flight hours was a significant predictor of on-duty disability. The study concluded that while military pilots are generally fit, the physical demands of flying can lead to significant musculoskeletal symptoms and disabilities. Enhanced physical training and better fitness assessments are recommended to maintain pilots' occupational health.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Shin, 2022 Pilot trainees' + 8.5 gz tolerance and fitness in their senior cadet period: a pilot study.	Observational Study (Cohort Study)	The study focuses on pilot trainees during their senior cadet period. These individuals are likely to be young adults, typically in good physical condition due to the demands of their training program. However, specific demographic details such as age range, gender distribution, or other characteristics are not provided in the context.	The exercise protocol likely involves activities designed to test and improve the trainees' tolerance to high gravitational forces, specifically +8.5 gz. This could include simulated flight conditions or other physical exercises that mimic the stresses experienced during high-speed maneuvers in flight. The exact details of the exercise protocol are not specified in the provided context.	The primary outcome measured in the study is the tolerance of pilot trainees to +8.5 gz forces. This is a critical factor in assessing their fitness and readiness for high-performance flying. Other potential outcomes, such as physiological responses or performance metrics, are not detailed in the context.	Contextual variables might include the trainees' baseline fitness levels, previous exposure to high-g environments, and any training interventions they have undergone. These factors can influence their ability to tolerate high gravitational forces. However, specific contextual variables are not mentioned in the provided context,	The study likely presents findings related to the ability of pilot trainees to withstand +8.5 gz forces, which is crucial for their roles as pilots. The key findings would provide insights into the effectiveness of their training programs and any areas that may require improvement. Unfortunately, the specific key findings are not detailed in the context provided.
Sung et al., 2023 Gravitational Acceleration Test Results by Lifestyle and Physical Fitness of Air Force Cadets.	Observational Study (Cross-sectional study)	The study focused on 138 fourth-year cadets from the Republic of Korea Air Force Academy (ROKAFA).	The specific exercise protocol details are not explicitly mentioned in the provided context. However, the study involved assessing physical fitness, which included measuring the 3-km running time and physical activity levels.	The primary outcome measured was the cadets' performance in the G test, which assesses G-LOC (G-induced Loss Of Consciousness) resistance. Additional outcomes included the analysis of the Three-Factor Eating Questionnaire (TFEQ) results, body composition, and physical fitness levels.	The study examined the relationship between lifestyle factors, such as eating behavior assessed by the TFEQ, and physical fitness with G test results. Body composition and physical activity levels were also considered as contextual variables influencing G test outcomes.	Statistically significant differences were found in the TFEQ results between the G test pass group (GP group) and the G test fail group (GF group). The GP group had a significantly faster 3-km running time and higher physical activity levels compared to the GF group. The study concluded that the TFEQ is useful in predicting G test outcomes, suggesting that improvements in eating behavior and physical fitness management are crucial for passing the G test. The research implies that continuous analysis and application of these variables in physical education and training could enhance G test success rates for cadets over the next two to three years.
Honkanen et al., 2020 Muscular Fitness Improves during the First Year of Academy Studies among Fighter Pilot Cadets.	Observational Study (Prospective Cohort Study)	The study focused on 182 male fighter pilot cadets. These cadets were in their first year at the Air Force Academy.	The study involved testing both muscular strength and endurance. Maximal isometric strength tests included: Trunk flexion Trunk extension Bilateral leg extension Muscle endurance was assessed using: A modified sit-up test Seated alternative dumbbell press.	The primary outcomes measured were changes in muscular strength and endurance over one year. Specific measurements included: Maximal isometric bilateral leg extensor strength Maximal isometric trunk extension and flexion strength Muscle endurance in terms of repetitions per minute in the sit-up test and dumbbell press .	The study was conducted within the context of the Air Force Academy's educational and physical training programs. The focus was on the first year of academy studies, a critical period for physical development in cadets.	There was a significant improvement in both maximal strength and muscular endurance among the cadets. Specific Improvements included: An increase in leg extensor strength from 220 ± 42 kg to 232 ± 42 kg. An increase in trunk extension strength from 117 ± 21 kg to 120 ± 19 kg. An increase in trunk flexion strength from 82 ± 16 kg to 86 ± 17 kg. Muscle endurance improved from 68 ± 13 to 75 ± 15 repetitions/min in the dumbbell press and from 47 ± 12 to 51 ± 13 repetitions/min in the sit-up test. The study concluded that the physical education and training provided at the Air Force Academy effectively improved the muscular fitness of the cadets, which is crucial for their occupational performance as military pilots.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Luo et al., 2024 Impact of a 12-wk physical conditioning program on the aerobic capacity of aviation cadets	Quasi-experimental (Interventional, non-randomized)	The study focuses on flight cadets, who are required to maintain high levels of physical fitness to meet the demands of flying missions. The continuous advancements in fighter jet technology have imposed new and higher physical fitness requirements on these individuals.	The paper discusses a 12-week physical conditioning program designed to enhance the aerobic capacity of aviation cadets. Although specific details of the exercise protocol are not provided in the context, it is implied that the traditional physical training methods are being reassessed to better meet current fitness needs.	The primary outcome measured in this study is the aerobic capacity of the aviation cadets. This is crucial as improved aerobic capacity can significantly impact the performance and endurance of cadets during flying missions.	The study is set against the backdrop of evolving fighter jet technology, which necessitates improved physical fitness standards for flight personnel. This context highlights the inadequacy of traditional training methods and the need for updated fitness programs.	The study suggests that traditional physical training methods are outdated and insufficient for meeting the current fitness requirements of aviation cadets. The study likely emphasizes the need for a revised training program that aligns with the modern demands of aviation technology and enhances the physical capabilities of cadets.
Balldin et al., 1985 Isometric abdominal muscle training and G tolerance	RCT (Randomized Controlled Trial)	The study involved 10 fighter pilots who were experienced in flying high-performance aircraft. These individuals were chosen due to their need for high G tolerance during flight Maneuvers.	The participants underwent an 11-week abdominal muscle training program. This program was designed to assess its impact on various physiological parameters related to G tolerance.	The study measured several outcomes, including: Maximal intra-abdominal pressure (IAP) G tolerance, assessed using a human centrifuge with simulated aerial combat maneuvers (ACM) Muscle strength and endurance, particularly focusing on the knee extensors	The study noted that the pilots had a higher maximal IAP before the training compared to a control group, which could influence the outcomes of the training program.	The abdominal muscle training program did not lead to significant changes in maximal IAP, G tolerance, or maximal peak torque of knee extensors. However, there was a notable increase in leg muscle endurance ($p < 0.01$) and a decrease in ratings of local perceived exertion ($p < 0.01$). A positive correlation was found between static endurance of the knee extensors and G tolerance ($p < 0.05$). The study concluded that the specific abdominal training program used was insufficient to enhance IAP or G tolerance in the experienced fighter pilots.
Tesch et al., 1983 Effects of strength training on G tolerance	RCT (Randomized Controlled Trial)	The study involved 11 fighter pilots. These individuals were selected due to their need for high G-tolerance when flying modern, high-performance fighter aircraft.	The participants underwent 11 weeks of muscle strength training. The specific exercises or regimen details are not provided, but the focus was on increasing muscle strength, particularly in the knee extensors.	The primary outcome was the increase in G-tolerance, assessed through simulated aerial combat maneuvers (ACM) in a human centrifuge. The ACM involved 15-second periods of exposure to 4.5 and 7 G until exhaustion. Secondary outcomes included changes in knee extensor muscle strength, anaerobic power, aerobic performance, and muscle histochemical indices from muscle biopsy samples of the m. vastus lateralis.	The study focused on neuromuscular adaptation as a potential mechanism for the observed improvements. This adaptation was linked to increased muscle strength and enhanced performance of the M-1 straining maneuver, which is crucial for G-tolerance.	The study found a 39% increase in ACM-time, indicating improved G-tolerance after the strength training program. There was a 17% increase in knee extensor muscle strength during slow contractions and a 14% increase in anaerobic power. No significant changes were observed in aerobic performance or muscle histochemical indices, suggesting that the improvements were primarily due to neuromuscular adaptations rather than changes in muscle composition or aerobic capacity.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Kölegård et al., 2013 Effects of physical fitness on relaxed G-tolerance and the exercise pressor response	Observational Study (Cross-Sectional Study)	The study involved three groups of male participants: Long-term endurance-trained (E; n = 17) Strength-trained (S; n = 16) Untrained (U; n = 17)	The exercise protocol included sustained (40 seconds) isometric knee extensions at 50% of the maximal contraction level to study the pressor response. Relaxed gradual onset-rate G-tolerance was also determined for each group.	The primary outcomes measured were: Relaxed G-tolerance Mean arterial pressure increase during isometric exercise.	The study considered the type of physical training (endurance vs. strength) and its duration (long-term, >6 months) as key variables influencing the outcomes.	Relaxed G-tolerance was found to be similar across all groups: endurance-trained (4.6 ± 0.5 G), strength-trained (4.9 ± 0.8 G), and untrained (4.6 ± 0.8 G). The mean arterial pressure increase during isometric exercise was higher in the strength-trained (36 ± 7 mmHg) and untrained (35 ± 16 mmHg) groups compared to the endurance-trained group (28 ± 8 mmHg). The results suggest that relaxed G-tolerance is not significantly affected by physical training habits. The training modality affects the magnitude of the exercise pressor response, with endurance training appearing to blunt the response rather than strength training enhancing it.
Crisman & Burton, 1988 Physical Fitness to Enhance Aircrew G Tolerance	Private Document	The study focuses on USAF/USN pilots, particularly those flying high-performance fighters. These pilots are involved in aerial combat maneuvers, which require enhanced G-duration tolerance to prevent G-induced loss of consciousness.	The exercise protocol described in the study involves a physical fitness program centered around resistance training, such as weightlifting. This program is designed to increase strength and anaerobic capacity. The study also discusses aerobic conditioning, highlighting precautions and limitations to ensure it does not negatively impact G tolerance.	The primary outcome measured is the increase in G-duration tolerance. This is crucial for pilots to withstand the high G-forces experienced during combat maneuvers without losing consciousness.	The study considers the specific needs of aviators, including the type of aircraft they operate and the maneuvers they perform. It also takes into account the physiological stress and exercise physiology related to acceleration tolerance.	The study finds that a structured weight-training program can effectively increase and maintain the strength and anaerobic capacity of pilots, thereby enhancing their G-duration tolerance. This improvement is vital for maintaining operational effectiveness and safety during high-stress aerial Maneuvers.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Balldin et al., 1994 Perceived exertion during submaximal G exposures before and after physical training.	Quasi-experimental (Interventional, Non-Randomized)	The study involved 17 pilots who participated in a combined strength and endurance training program. These individuals were likely selected due to their need for high physical performance and endurance in their professional roles.	The pilots underwent a 12-month physical training program that combined strength and endurance exercises. This program was designed to improve their endurance G tolerance, which is crucial for their performance during aerial combat maneuvers.	Ratings of Perceived Exertion (RPE): RPE was measured at submaximal levels during G endurance tests. This metric helps in understanding the subjective effort and fatigue experienced by the pilots during the tests. Endurance G Tolerance: This was assessed by measuring the time to exhaustion during simulated aerial combat maneuvers. It is a critical outcome as it directly relates to the pilots' ability to withstand high G forces. Oxygen Saturation (SaO_2): Mean SaO_2 was measured at 5 minutes into the submaximal G exposure to assess the pilots' oxygenation levels during the tests. Heart Rate Responses: Although measured, heart rate responses to G stress did not show significant changes post-training.	Training Duration: The study spanned 12 months, allowing for a comprehensive assessment of the long-term effects of the training program on the pilots' performance and physiological responses.	Improvement in Endurance G Tolerance: After 12 months of training, the endurance G tolerance increased by a mean of 40%, indicating a significant enhancement in the pilots' ability to withstand G forces ($p < 0.001$). Decrease in RPE: The mean RPE at 5 minutes of submaximal G exposure decreased by 1.2 units, suggesting that the pilots perceived less exertion after the training ($p < 0.02$). Increase in SaO_2: Mean SaO_2 at 5 minutes increased from 84% to 90%, indicating improved oxygenation during G exposure ($p < 0.01$). Relationship Between Improvements: A significant relationship was found between the improvement in endurance G tolerance and the decrease in RPE at 5 minutes ($p = 0.05$), suggesting that perceived exertion could be a useful indicator of endurance improvements.
Epperson et al., 1985 The effectiveness of specific weight training regimens on simulated aerial combat maneuvering G tolerance	RCT (Randomized Controlled Trial)	The study involved seven young men who participated in the research to assess the impact of weight training on G tolerance during simulated aerial combat maneuvering (SACM).	Participants underwent a 12-week whole-body weight training program. The training focused on increasing muscle strength across various muscle groups, including abdominal and biceps muscles.	The study measured several outcomes: Muscle strength, particularly in the abdominal (sit-ups) and biceps (arm curl) areas. Body circumferences, including chest, biceps, abdomen, and thighs. Body mass and percentage of body fat. SACM G tolerance, defined as the total time a subject could withstand continuous exposure to a 4.5 and 7.0 + Gz centrifuge Profile.	The study considered changes in body composition, such as increases in muscle circumferences and decreases in body fat, as contextual variables that might influence SACM tolerance.	There was a significant increase in muscle strength, with abdominal strength increasing by 99% and biceps strength by 26.2%. These increases were highly correlated with improved SACM tolerance time ($p < 0.01$). Chest and biceps circumferences increased by 4.2% and 3.1%, respectively, while body fat decreased by 16.8%, and body mass increased by 2.3%. The study found a net increase in SACM tolerance times of 53% as a result of the weight-training program. A multiple regression analysis showed a correlation of determination of 0.61 between the strength of all four muscle groups and SACM tolerance over the 12 weeks.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Ding et al., 2024 Evaluating the impact of a combined aerobic and strength training intervention on the physical performance of male Chinese People's Liberation Army air force pilots	Experimental Study (Pre-post design)	The study involved 20 male Air Force pilots. Average age: 31.87 ± 2.75 years. Average body mass: 76.33 ± 0.79 kg. Average height: 175.55 ± 3.65 cm.	The intervention was a 16-week combined training program. It included both aerobic and strength training. Participants engaged in six weekly training sessions.	Estimated maximal oxygen uptake (VO_2 max). Maximal strength (handgrip strength for both hands, squat maximal strength). Muscular endurance (push-ups, sit-ups). Long jump performance	Participants were categorized into two groups based on their initial physical performance levels to assess baseline influences on post-intervention adaptations.	Significant improvements were observed in all measured outcomes after the training program. VO_2 max showed a significant increase (F = 86.898; $p < 0.001$; ηp^2=0.821ηp^2=0.821). Handgrip strength improved significantly for both right (F = 160.480; $p < 0.001$; ηp^2=0.894 ηp^2=0.894) and left hands (F = 102.196; $p < 0.001$; ηp^2=0.843 ηp^2=0.843). Squat maximal strength (F = 525.725; $p < 0.001$; ηp^2=0.965 ηp^2=0.965), push-ups (F = 337.197; $p < 0.001$; ηp^2=0.974 ηp^2=0.974), sit-ups (F = 252.500; $p < 0.001$; ηp^2=0.930 ηp^2=0.930), and standing long jump (F = 521.714; $p < 0.001$; ηp^2=0.965 ηp^2=0.965) all showed significant improvements. The training regimen significantly enhanced physical performance regardless of initial performance levels.
Kim et al., 2022 Analysis of G-test Results According to Fatigue, Physical Fitness and Body Composition of Air Force Cadets Using Smart Watches	Observational Study (Cross-Sectional Study)	The study focused on 27 fourth-grade cadets from the Air Force Academy. These individuals were selected to analyze their G-test results, which are crucial for understanding their ability to withstand gravitational forces during flight.	The paper does not provide specific details about an exercise protocol. However, it mentions the use of wearable devices to measure heart rate and fatigue, which suggests that the cadets were monitored during their regular activities or specific tests.	The study measured several outcomes, including heart rate, fatigue, and body composition. The G-test results were analyzed to determine the relationships among these variables. Significant differences were found in heart rate, deep sleep time, and fatigue levels, indicating their impact on G-resistance,	The study considered various physiological changes experienced by cadets in an aerial environment, such as gravity-induced loss of consciousness (G-LOC), hypoxia, and flight disorientation. These factors are critical as they affect the cadets' ability to withstand high gravitational forces, which is essential for their training and Safety.	The study concluded that improving aerobic performance, managing fatigue, and enhancing physical fitness are essential for successful G-test outcomes. It suggests that continuous research and application of findings in physical education and training could improve G-tolerance in cadets over the next 2-3 years. The study also highlights the importance of G-resistance, which is the ability to withstand gravitational forces without losing consciousness, as a crucial factor for pilot safety and effectiveness.

+Gz – Positive gravitational force along the vertical (head-to-foot) axis; ACP – Aircrew Conditioning Programme; AGSM – Anti-G Straining Maneuver; BMI – Body Mass Index; BP – Blood Pressure; CLT – Cervical Loading Testing; EAW – Equivalent Annual Worth; EMG – Electromyography; FFS – Feeling of Fatigue Scale; G-LOC – G-induced Loss of Consciousness; Gz – Gravitational force on the vertical axis; HR – Heart Rate; IAP – Intra-Abdominal Pressure; MP – Mean Power; PBG – Positive Pressure Breathing (for G protection); PP – Peak Power; RCT – Randomized Controlled Trial; RGT – Relaxed G Tolerance; RPE – Rating of Perceived Exertion; SACM – Simulated Aerial Combat Maneuver; SaO_2 – Arterial Oxygen Saturation; SGT – Straining G Tolerance; STG – Strength Training Group; TFEQ – Three-Factor Eating Questionnaire; TTG – Trampoline Training Group; U – Untrained group; VAS – Visual Analog Scale; VO_2max – Maximum Oxygen Uptake; WT – Wingate Test

Appendix S9. Details of studies and information relevant to Equipment and Technology for Enhancing G-Tolerance

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Ui et al., 1996 Centrifuge man-rating of a conceptual internal abdominal bladder restraint in an extended coverage anti-G suit	RCT (controlled trial)	The study involved four Swedish test fighter pilots. These individuals were selected to evaluate the effects of an internal abdominal bladder restraint in the Swedish Tactical Flight Combat Suit (TFCS).	The tests were conducted using the Armstrong Laboratory Centrifuge at Brooks AFB. The centrifuge profiles included: Gradual onset runs (GOR) where subjects were relaxed. Rapid onset runs (ROR) where subjects were straining. Simulated aerial combat maneuver (SACM) runs, which went up to +9 Gz until subjects experienced light loss, fatigue, or surpassed 228 seconds.	The primary outcomes measured were: +Gz tolerance during GOR and ROR runs. Duration of SACM runs. Incidence of abdominal pain or discomfort. Ratings of perceived exertion after multiple peaks at +9 Gz. Subjective +Gz tolerance. Overall comfort, fatigue, and heat stress.	The study considered the use of pressure breathing during G (PBG) in conjunction with the TFCS. The presence or absence of the abdominal bladder restraint was a key variable in assessing its impact on comfort and performance.	All subjects withstood 60 seconds at +9 Gz during both GOR and ROR runs, regardless of the presence of the abdominal bladder restraint. There was no difference in SACM duration times with or without the bladder restraint. In three out of four subjects, abdominal pain or discomfort experienced without the bladder restraint disappeared when it was used. Ratings of perceived exertion, subjective +Gz tolerance, overall comfort, fatigue, and heat stress showed no significant differences with or without the bladder restraint. The study concluded that it is possible to modify the TFCS by adding an abdominal bladder internal restraint to enhance comfort without compromising operational +Gz protection.
Travis & Morgan, 1994 US Air-force positive-pressure breathing anti-g system (PBG) - subjective health-effects and acceptance by pilots	Observational Study (Cross-sectional Study	The study surveyed 241 pilots from the U.S. Air Force, specifically those flying F-15 and F-16 aircraft. Among these, 49 pilots were using the positive-pressure breathing anti-G system (PBG), while 192 pilots were using standard anti-G methods.	The study did not specify a detailed exercise protocol but focused on the operational use of the PBG system during flights in high-performance fighter aircraft. The PBG system is part of the COMBAT EDGE program, designed to enhance anti-G support for aircrew.	The primary outcomes measured were acute health effects and the impact of the PBG system on mission accomplishment. The study specifically looked for any significant increases in adverse health events among pilots using the PBG system.	The type of aircraft (F-15 vs. F-16) was a significant contextual variable, as acceptance of the PBG system varied between these two groups. The study also considered the standard anti-G methods as a comparison group to evaluate the effectiveness and acceptance of the PBG system.	The study found no significant increases in adverse health events with the use of the PBG system, except for a noted increase in dry cough among pilots. Acceptance of the PBG system was much greater among F-16 pilots compared to those flying the F-15, indicating a possible difference in system integration or pilot preference between the two aircraft types.
Oksa et al., 2003 The effect of lumbar support on the effectiveness of anti-G straining maneuvers	Randomized Controlled Trial (RCT)	The study involved eleven fighter pilots. These individuals were selected due to their need to perform efficient anti-G straining maneuvers (AGSM) to enhance their G-tolerance during flight operations.	The pilots participated in four AGSM training sessions. Each session included 4-5 repetitions, with each repetition lasting approximately 10 seconds. The sessions were conducted under different conditions: without lumbar support and with lumbar supports of varying thicknesses (7 mm, 14 mm, and 26 mm).	The primary outcomes measured were the average electromyogram (aEMG) and power spectrum area (PSA) of eight muscles: rectus and biceps femoris, gluteus maximus, erector spinae, rectus abdominis, obliquus externus, latissimus dorsi, and pectoralis major. These measurements were used to assess the effectiveness of the AGSM.	The study considered the presence or absence of lumbar support as a key variable. The thickness of the lumbar support (7 mm, 14 mm, and 26 mm) was varied to determine its impact on the effectiveness of AGSM.	The use of lumbar support increased the effectiveness of AGSM. Specifically, in a single best AGSM, the aEMG increased by 12%, 10%, and 14%, and the PSA increased by 20%, 26%, and 44% with 7 mm, 14 mm, and 26 mm supports, respectively, compared to no support. The effectiveness, as measured by aEMG and PSA, increased in 11 and 10 subjects, respectively, with average increases of 12% (aEMG) and 25% (PSA). During repeated AGSM sessions, the effectiveness was highest with lumbar support in 7 subjects, while 4 subjects performed better without it. Overall, the average increase in effectiveness during repeated AGSM was 6% (aEMG) and 11% (PSA).

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Balldin et al., 2003 Endurance and performance during multiple intense high plus Gz exposures with effective anti-G protection	Experimental Study (Controlled Study)	The study involved nine well-trained centrifuge subjects. These individuals were likely selected for their ability to endure high-stress conditions similar to those experienced by fighter pilots during intense aerial maneuvers.	Subjects were exposed to tactical aerial combat maneuvers using balanced pressure breathing during G (PBG) and an extended coverage anti-G suit. The protocol included five simulated sorties over a 4-hour period. Each sortie consisted of four engagements with rapid onset cycles ranging from +4 Gz to +9 Gz.	The study measured several physiological and performance outcomes: Effort level on a scale from 0 (no effort) to 11 (maximum effort). Maximal heart rate, which varied from 140 to 173 beats per minute (bpm). Minimum finger oxygen saturation, ranging from 75% to 93%. Maximal peripheral and central light-loss, with means of 71% and 40%, respectively. Incidences of G-induced Loss Of Consciousness (G-LOC) and near loss of consciousness. Recovery time from general fatigue, which varied from 9 to 48 hours. Performance on a tracking task before, during, and after each engagement. Neck muscle strength before and after the test.	The study was conducted under controlled conditions using a centrifuge to simulate the high +Gz forces experienced during aerial combat. The use of PBG and an extended coverage anti-G suit were key variables in assessing the endurance and performance of the subjects.	Seven out of nine subjects were able to endure all five sorties within the 4-hour period. Performance deteriorated significantly during G exposures, and neck muscle contraction was impaired by 12% after the G exposure. The study concluded that it is possible to train subjects to withstand multiple high +Gz exposures using the specified anti-G protection methods.
Ui & J, 1992 G-endurance during heat-stress and balanced pressure breathing	Experimental Study (Controlled Study)	The study involved ten fighter pilots as participants. These pilots were equipped with anti-G-suits that had increased bladder coverage.	Participants were subjected to heat stress, with their body temperature raised to 38.2°C. They were exposed to 15-second periods at 4.5 and 7 G in a heated human centrifuge gondola. The exercise was conducted until exhaustion during two conditions: balanced pressure breathing (PBG) and normal breathing (NB).	The primary outcome measured was G-endurance, which is the duration the pilots could withstand the G-forces. Other outcomes included rectal temperature, dehydration levels, oxygen saturation, ratings of perceived exertion, and maximum heart rate	Heat stress was a significant variable, with rectal temperature rising to a mean of 38.3°C. Dehydration was also noted, with an average weight loss of about 1.2 kg due to fluid loss.	G-endurance was slightly higher with PBG (300 seconds) compared to NB (254 seconds), although this difference was not statistically significant. Oxygen saturation and perceived exertion ratings remained largely unchanged between the two breathing conditions. A notable finding was the decrease in maximum heart rate by an average of 13 beats per minute during PBG compared to NB. The study concluded that G-endurance was not negatively affected by PBG during heat stress, but it highlighted the importance of managing heat stress and dehydration during G-loads

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Eiken et al., 2002 A new hydrostatic anti-G suit vs. a pneumatic anti-G system: preliminary comparison.	Randomized Controlled Trial (RCT)	The paper does not provide specific details about the population characteristics involved in the study. Typically, studies on anti-G suits involve participants who are pilots or individuals exposed to high +Gz forces, but this is not explicitly mentioned in the provided context.	The context does not detail the specific exercise protocol used in the study. Generally, such studies might involve simulations or real-life scenarios where participants are subjected to varying levels of +Gz forces to test the effectiveness of the anti-G suits.	The primary outcome of interest in this study is the level of protection against +Gz acceleration provided by the new hydrostatic anti-G suit compared to a pneumatic anti-G system. The abstract suggests that the hydrostatic suit is commercially available and claims to offer high protection levels, but specific outcome measures are not detailed in the context provided.	The context does not specify the variables considered in the study. In general, studies of this nature might consider variables such as the duration of exposure to +Gz forces, the maximum +Gz force tolerated, physiological responses, and subjective comfort levels.	The abstract hints at a comparison between a new hydrostatic anti-G suit and a traditional pneumatic anti-G system. However, it does not provide specific findings or results from the comparison. The focus seems to be on the potential high level of protection offered by the hydrostatic suit, but without detailed results or data.
Wood et al., 1990 Partial supination versus Gz protection	Randomized Controlled Trial (RCT)	The study involved untrained pilots, with a total of 41 participants. Specifically, 14 pilots were tested with a 5-second duration at 2 G/s onset G forces, and 27 pilots were tested with a 10-second duration under the same conditions	The protocol involved exposing pilots to G forces with varying body positions. The pilots were tested in both upright and supinated positions, with supination angles of 60 degrees and 45 degrees being specifically mentioned.	The primary outcomes measured were visual symptoms and loss of consciousness (G-LOC) during the G force exposure. The study aimed to assess the tolerance levels of pilots to these forces under different body orientations.	The study considered the angle of supination as a key variable, with specific attention to the effects of 30, 45, and 60-degree supination on G tolerance. The unexpected results at 45 degrees and the slight decreases in tolerance at 30 degrees were highlighted as significant findings.	The study found that pilots had high tolerance to G forces when upright, with an increase in tolerance of more than 3 G when supinated to 60 degrees. However, protection against visual symptoms was only 1.1 G at 60 degrees, and there was no protection at 45 degrees for experienced subjects, which was unexpected. The findings suggested that factors other than the heart-to-brain distance, such as increased intracranial and intraocular pressures, might affect G tolerance when subjects are supinated at 30 degrees. The study concluded that the increased incidence of G-LOC since the introduction of 30-degree seats in fighter jets like the F-16 supports the relevance of these findings. It was recommended that aircrew should adopt the practice of sitting upright during high G maneuvers, as done by veteran test pilots.

+Gz – Positive gravitational force on the vertical axis (head-to-foot); aEMG – Average Electromyogram; AFB – Air Force Base; AGSM – Anti-G Straining Maneuver; BMI – Body Mass Index; COMBAT EDGE – Combined Advanced Technology Enhanced Design G Ensemble (USAF anti-G system); FFS – Feeling of Fatigue Scale; GOR – Gradual Onset Run; G-LOC – G-induced Loss of Consciousness; HQ – Headquarters; HR – Heart Rate; IAP – Intra-Abdominal Pressure; NB – Normal Breathing; PBG – Positive Pressure Breathing (during G); PSA – Power Spectrum Area; RCT – Randomized Controlled Trial; RER – Ratings of Perceived Exertion; ROR – Rapid Onset Run; RPE – Rating of Perceived Exertion; SACM – Simulated Aerial Combat Maneuver; SaO_2 – Arterial Oxygen Saturation; STG – Strength Training Group; TFCS – Tactical Flight Combat Suit; TFEQ – Three-Factor Eating Questionnaire; TTG – Trampoline Training Group; VAS – Visual Analog Scale; VO_2max – Maximal Oxygen Uptake; WT – Wingate Test

Appendix S10. Details of studies and information relevant to Risks and Impacts of High-G Environments on Pilots

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Galvagno et al., 2004 Acceleration risk in student fighter pilots: Preliminary analysis of a management program	Observational Study (Retrospective Cohort Study)	The study focuses on F-16 student pilots at Luke Air Force Base. These pilots are undergoing training and are subject to G-performance evaluations.	The GRIM Program includes assessments of anthropomorphic data, previous G-performance, anaerobic fitness, and centrifuge qualification scores. These assessments are used to tailor ground training programs aimed at improving G-performance.	The primary outcomes measured include anaerobic test scores, centrifuge scores, and qualitative observations from gradebook comments. These outcomes help in determining the level of risk for each student pilot.	The study lacks historical controls, which limits the ability to draw definitive conclusions about the program's overall efficiency. The absence of historical data makes it challenging to compare current results with past performance.	Significant differences were observed between groups in terms of anaerobic test scores, centrifuge scores, and gradebook comments. The study suggests a need for future research to better validate the G-risk indicators used in the program. The non-experimental nature of the study indicates preliminary findings, highlighting the importance of further investigation to establish the program's effectiveness.
Rickards & Newman, 2005 G-induced visual and cognitive disturbances in a survey of 65 operational fighter pilots	Observational Study (Cross-Sectional Study)	The study surveyed 65 operational fighter pilots from the Royal Australian Air Force (RAAF). The age range of the pilots was 20-53 years. Heights ranged from 168 to 193 cm, and weights from 64 to 110 kg. The pilots had between 30 to 5700 hours of jet flying experience.	The survey focused on pilots flying the F/A-18 and Hawk 127 aircraft. These aircraft can produce +Gz accelerations up to +7.5 Gz, which is a significant factor in the study of G-induced disturbances.	The survey collected data on G-induced visual and cognitive disturbances. Specific symptoms of almost loss of consciousness (A-LOC) and G-induced loss of consciousness (G-LOC) were recorded. The survey also gathered information on the type of aircraft, flying maneuvers performed, and mission outcomes.	The study considered the type of aircraft and the specific flying maneuvers as contextual variables. The mission outcomes were also analyzed to understand the impact of G-induced disturbances on operational effectiveness.	A significant 98% of pilots reported experiencing at least one visual or cognitive disturbance in high G environments. Specific disturbances included gray-out (98%), black-out (29%), and A-LOC symptoms (52%). A-LOC symptoms included abnormal sensations in limbs, disorientation, and confusion. 9% of pilots experienced G-LOC, with half of these incidents occurring while the pilot was flying the aircraft. The incidence of A-LOC among RAAF pilots was notably higher compared to other studies of operational fighter pilots.
Yilmaz et al., 1999 Visual symptoms and G-LOC in the operational environment and during centrifuge training of Turkish jet pilots	Observational Study (Retrospective Cohort Study)	The study focused on Turkish jet pilots who operate F-16, F-4, and F-5 aircraft. A total of 325 pilots participated in the survey, categorized by the aircraft they currently fly: 116 F-16 pilots, 182 F-4 pilots, and 27 F-5 pilots. These pilots had experience flying T-37 aircraft during their undergraduate pilot training (UPT).	The research was divided into two parts: a survey and centrifuge training. The survey aimed to assess the incidence of visual symptoms and G-induced loss of consciousness (G-LOC) during +Gz acceleration in operational environments. Centrifuge training was conducted at the Turkish Aerospace Medical Center from 1992 to 1996 to evaluate G-LOC rates among pilots.	The primary outcomes measured were the incidence of visual symptoms (greyouts and blackouts) and G-LOC. The study also measured the frequency of G-LOC during centrifuge training for different aircraft types.	The type of aircraft flown by the pilots was a significant variable, influencing the frequency of G-LOC. The study considered the rapid onset rate of G-forces in different aircraft as a factor affecting G-LOC occurrence.	Almost all pilots (95.7%) reported experiencing visual symptoms related to +Gz forces. G-LOC was more common in pilots flying aircraft with rapid onset rates, such as the F-16, compared to those flying aircraft with lower G onset rates, like the F-4 and F-5. The frequency of G-LOC was highest in centrifuge training for F-5 pilots (8.6%), followed by F-4 (6.4%) and F-16 (12%). Centrifuge training was found to reduce G-LOC rates in subsequent training sessions, suggesting potential benefits for operational flight safety.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Linde & Balldin, 1998 Arm pain among Swedish fighter pilots during high +Gz flight and centrifuge exposures	Observational Study (Cross-Sectional Study)	The study involved 35 Swedish Air Force Viggen and Gripen fighter pilots. These pilots had previously participated in centrifuge tests between 1990 and 1995 at Brooks Air Force Base, Texas. The participants were either using the standard anti-G suit or an extended coverage anti-G suit with pressure breathing during +Gz exposure.	The pilots were exposed to high +Gz loads during both actual flight and centrifuge tests. The centrifuge tests were conducted to simulate the high +Gz conditions experienced during flight, allowing for controlled observation of physiological responses.	The primary outcome measured was the occurrence of arm pain associated with high +Gz exposure. The study aimed to determine the frequency and conditions under which arm pain occurred during both flight and centrifuge tests.	The type of anti-G suit used (standard vs. extended coverage with pressure breathing) was a significant variable. The study also considered the different environments of actual flight versus centrifuge testing as contextual variables influencing the occurrence of arm pain.	55% of the pilots reported experiencing arm pain during flight at least once, with 42% experiencing it more than three times. Arm pain was more prevalent during centrifuge tests, with 82% of pilots experiencing it at least once and 42% more than three times. The study concluded that arm pain is a significant issue during high-performance fighter aircraft flights and should be considered in the design of aircraft and protective equipment.
Jones et al., 2000 Human and behavioral factors contributing to spine-based neurological cockpit injuries in pilots of high-performance aircraft: Recommendations for management and prevention	Observational Study (Retrospective Cohort Study)	The study surveyed pilots from various aircraft types, including T-38, F-14, F-15, F-16, and F/A-18 fighters. A total of 95 surveys were administered, with 58 full responses. The study focused on high-performance jet aircraft (HPJA) pilots, who are at risk for spine-based injuries due to high-g Maneuvers.	The study evaluated the impact of pre-flight stretching and regular weight training on reducing neck pain. It was found that pre-flight stretching did not significantly reduce neck pain episodes. However, regular weight training showed a trend towards reducing pain, especially in F/A-18 pilots, although it was not statistically significant.	The primary outcomes measured were the prevalence and severity of cervical spine injuries and pain episodes among pilots. The study also assessed the effectiveness of different preventive strategies, such as stretching and weight training, in reducing these outcomes .	Several factors were considered, including the type of aircraft, cockpit ergonomics, pilot behavior during high-g turns, and the use of flight equipment. The study also looked at the impact of head and body position during maneuvers and the role of pre-flight and in-flight habits on injury risk.	A significant number of pilots reported experiencing in-flight or post-flight spine-based pain, with 90% of fighter pilots having at least one event. Pain was most commonly reported during high-g turns with the head in a non-neutral position. Pre-flight stretching did not significantly reduce pain episodes, while regular weight training showed a potential benefit, particularly in F/A-18 pilots. The study highlighted the need for improved cockpit design and preventive strategies to reduce the risk of spine injuries in pilots.
Kadozono et al., 2024 Seat angle effects on disc degeneration for pilots in high-g environments	Observational Study (Retrospective Cohort Study)	The study focuses on pilots, particularly those operating in high-G environments such as F-16 pilots. These individuals are frequently exposed to high gravitational forces during both training and operational missions, which can lead to spinal issues.	The research utilizes the Toyota Human Model for Safety (THUMS) to simulate the effects of different seat angles on intervertebral discs. The loading profile used in the study mirrors the forces experienced during centrifuge training, which is a common method for preparing pilots for high-G environments.	The primary outcome measured in the study is the effective stress on intervertebral discs, which is used to calculate the fatigue damage over time. This measurement helps in understanding how different seat angles can impact disc degeneration under high-G conditions.	The study considers the seat angle as a critical variable, as its impact on disc degeneration during high-G maneuvers is not well understood. The research aims to fill this gap by investigating how varying seat angles affect the stress and potential damage to the Spine.	The study highlights the importance of understanding seat angle effects to develop effective training programs and preventive measures. By identifying how seat angles influence disc degeneration, the research aims to reduce the risk of spinal abnormalities in pilots, thereby protecting their health during both training and operational missions.
Slungaard et al., 2017 Incidence of G-Induced Loss of Consciousness and Almost Loss of Consciousness in the Royal Air Force	Observational Study (Retrospective Cohort Study)	The study involved all Royal Air Force (RAF) pilots and weapons systems operators (WSOs), totaling 2,351 individuals (1,878 pilots and 473 WSOs).	The study did not focus on an exercise protocol per se but involved a survey methodology. An anonymous questionnaire was distributed to gather data on G-induced loss of consciousness (G-LOC) and almost loss of consciousness (A-LOC) events among the aircrew.	The primary outcomes measured were the incidence rates of G-LOC and A-LOC events among the RAF aircrew. The study aimed to compare these rates with those from a previous survey conducted in 2005.	The study considered the type of aircraft flown, as there was an increased reporting of G-LOC and A-LOC in specific aircraft like the Hawk, Tucano, and Grob Tutor. The introduction of interventions such as centrifuge training and the anti-G straining maneuver (AGSM) were also contextual variables influencing the outcomes.	The prevalence of reported G-LOC decreased compared to the 2005 survey, suggesting a positive impact of the interventions introduced, such as centrifuge training. However, there was an increase in G-LOC and A-LOC events reported in certain aircraft, indicating areas for further improvement. The study highlights the importance of early centrifuge training and a structured conditioning program to enhance the effectiveness of AGSM and reduce G-LOC incidents further.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Shender et al., 2003 Acceleration-induced near-loss of consciousness: the "A-LOC" syndrome	Observational Study (Descriptive Study	The study involved nine subjects who were exposed to varying levels of +Gz stress. These subjects were likely aircrew or individuals trained to withstand high G-forces, as the study focused on the effects of acceleration-induced stress relevant to Aviation.	Subjects were exposed to short pulses of +6, +8, and +10 Gz, with increasing duration until they experienced G-LOC (G-induced Loss of Consciousness). This protocol was designed to simulate the conditions under which A-LOC (Almost Loss of Consciousness) might occur.	The study measured a variety of outcomes, including: Cognitive symptoms such as short-term memory loss and confusion. Physical symptoms like sensory abnormalities and difficulty in forming words. Emotional responses, including euphoria. Physiological changes, particularly in cerebral tissue oxygenation (rSo2), using near-infrared spectroscopy (NIRS).	The study considered the relationship between the symptoms of A-LOC and the underlying physiological changes, particularly focusing on the reduction and recovery of cerebral oxygenation levels during and after +Gz exposure.	A-LOC is characterized by a wide range of symptoms, including sensory abnormalities, amnesia, confusion, euphoria, and reduced auditory acuity. A significant finding was the disconnection between cognition and the ability to act on it, which was a common symptom among subjects. Physiologically, there was a notable reduction in cerebral tissue oxygenation during +Gz stress, with a greater overshoot in oxygenation levels above baseline after the exposure, and a prolonged recovery time compared to +Gz exposures without symptoms. The study suggests that understanding these symptoms and their physiological basis can help in developing programs to increase pilots' awareness of A-LOC and improve safety in aviation.
Alvim, 1995 Greyout, blackout, and G-loss of consciousness in the Brazilian Air Force: a 1991-92 survey.	Observational Study (Cross-Sectional Study)	The study involved high and medium performance aircraft pilots from the Brazilian Air Force. Pilots from various aircraft squadrons, including F-5, AMX, Mirage F-103, Xavante AT-26, and Tucano T-27, participated. A total of 193 pilots responded to the survey	The study did not specify a particular exercise protocol but focused on the incidence of symptoms due to +Gz acceleration during flight maneuvers. The aim was to develop a human centrifuge physiological training profile tailored to the needs of these pilots.	The survey measured the occurrence of visual symptoms such as greyout and blackout, as well as loss of consciousness (G-LOC) during +Gz maneuvers. Post-G-LOC symptoms were also recorded, with a distinction between gradual and instantaneous recovery.	The type of aircraft flown was considered, but the incidence of G-LOC was found to be independent of the aircraft type ($p > 0.05$).	11.92% of pilots reported experiencing greyout and/or loss of peripheral vision. 20.72% reported experiencing blackout. 10.36% reported experiencing G-LOC. All pilots who reported G-LOC also experienced post-G-LOC symptoms, with 80% having a gradual recovery and 20% an instantaneous recovery. 80% of those who experienced G-LOC were preceded by a blackout, suggesting a potential opportunity to mitigate the effects by reducing +Gz load before reaching the G-LOC endpoint. The study recommends intensive human centrifuge training, similar to hypoxia-recognition tests, for pilots to safely recognize their consciousness endpoint during +Gz maneuvers.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Sevilla & Gardner, 2005 G-induced loss of consciousness: case-control study of 78 G-Locs in the F-15, F-16, and A-10.	Observational Study (Case-control Study)	The study focused on USAF pilots who experienced G-induced loss of consciousness (G-LOC) mishaps from 1980 to 1999. A total of 2002 mishap pilots were included, with specific attention to those flying F-16, F-15, F-15E, and A-10 aircraft. Key characteristics examined included pilot age, height, weight, BMI, total flight hours, hours in the specific aircraft, and sortie history.	The study did not specify an exercise protocol as it was observational, focusing on real-world mishaps rather than controlled exercises. The emphasis was on identifying trends and risk factors associated with G-LOC incidents rather than testing specific interventions or protocols.	The primary outcome was the occurrence of G-LOC mishaps. The study also measured the frequency of poor anti-G straining maneuvers, fatigue, G-suit malfunctions, and low G-tolerance among pilots.	The study considered various contextual variables such as the type of aircraft, pilot experience in terms of flight hours, and age. It also looked at the role of training and the experience level of pilots, particularly those new to the aircraft.	G-LOC mishaps accounted for only 2.5% of all mishaps during the study period. A significant finding was that pilots with less than 600 hours in the F-16 had a 3.5 times greater chance of experiencing a G-LOC mishap, and those in the F-15 had a 9.5 times greater chance. Younger pilots, particularly those under 30, were at higher risk, with a 4.5 times greater chance in the F-16 and a 3 times greater chance in the F-15. Poor anti-G straining maneuvers were a common factor in 72% of the mishaps, highlighting the need for improved training and prevention strategies.
Gawron, 1997 High-g Environments and the Pilot.	Theoretical Article	The paper mentions that 10% to 30% of all fighter pilots worldwide have experienced g-induced loss of consciousness (g-LOC). In the U.S. Air Force, two g-LOC episodes occur every month during undergraduate pilot training.	The paper does not provide specific details about an exercise protocol. However, it mentions that weight training may extend simulated air combat maneuvering time up to 300 seconds, suggesting that physical conditioning is a factor in g tolerance.	The outcomes measured include the duration of incapacitation following g-LOC, which can last from 15 seconds for one exposure to 20 seconds after five exposures. Performance decrements are also measured, such as increased time to trim an aircraft after g-LOC and changes in tracking performance under increased +gz.	Several factors affect g tolerance, including chronic and acute hypertension, high temperature, hypoxia, hypoglycemia, stress, dehydration, and more. Human factors such as expectation, individual tolerance, eye-heart vertical distance, age, and the use of anti-g straining maneuvers (AGSM) and positive pressure breathing (PPB) are also important. The use of g-suits and head position during g exposure are additional variables that influence g tolerance.	The paper highlights that g-LOC is a significant risk for fighter pilots, with a notable percentage experiencing it during their careers. The duration of incapacitation and performance decrements are influenced by the number of g exposures and the rate of g onset. Various human and equipment factors can enhance or reduce g tolerance, such as physical conditioning, g-suits, and AGSM.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Hormeño-Holgado & Clemente-Suárez, 2019 Effect of different combat jet maneuvers in the psycho-physiological response of professional pilots.	Experimental Study (Non-Randomized)	The study involved 29 fighter pilots from the Spanish Air Forces. They were relatively young with an average age of 28.3 years, an average height of 178.5 cm, and weighing about 75.3 kg. These pilots had, on average, 9.4 years of professional flying experience. Many had participated in international missions in various conflict zones such as Lebanon, Afghanistan, Bosnia, Kosovo, and Iraq.	Two types of air combat maneuvers were evaluated: offensive and defensive. Both maneuvers were conducted using an F5 combat aircraft. The offensive maneuver involved starting from a one-mile separation, reaching speeds up to 400 knots, and engaging in rapid ascension and deceleration, which imposed various G forces ranging approximately from 0.5 to 5.9 G's during the combat flight. The defensive maneuver included turn maneuvers and break turns, with the aircraft flying at speeds around 350 knots and encountering varying G forces that decreased during the maneuvers. Measurements were taken just two hours before and thirty minutes after the maneuvers. During the experiments, several physical and psychological tests were conducted onboard the aircraft and shortly after the flight.	The study included a variety of physiological and psychological outcomes. Physiological variables: Heart Rate (both mean and maximum), heart rate variability (HRV) parameters (such as RMSSD, PNN50), spirometry tests to measure forced vital capacity (FVC), isometric hand strength (IHS), lower body strength via horizontal jump tests, body temperature, blood oxygen saturation (BOS), and blood lactate levels. Psychological outcomes: Cognitive anxiety, somatic anxiety, perceived exertion (RPE on the Borg scale), stress subjective perception (SSP), and state anxiety were assessed using standardized questionnaires such as CSAI-2R and STAI-based scales. Additional parameters included assessments of cortical arousal and short-term memory tests.	Environmental factors played a significant role: the maneuvers were conducted at altitudes between 8000 and 18,000 feet, thereby subjecting pilots to hypobaric conditions where oxygen partial pressure decreases leading to hypoxia. G forces varied dynamically during different phases of the flight, influencing the pilots' physiological responses such as cardiovascular activation and muscle fatigue. The specific flight conditions, including duration (approximately 30–40 seconds for key segments, with entire maneuvers lasting about 30–35 minutes), and the use of oxygen mixes at altitudes above 8000 ft, were critical contextual variables that may have affected the outcomes.	Both offensive and defensive maneuvers resulted in significant increases in heart rate and perceived stress/effort levels. In contrast, blood oxygen saturation decreased during both types of maneuvers. Specifically for the defensive maneuver, there was a noted decrease in forced vital capacity (a measure of lung strength) and urine specific gravity, along with an increase in leg strength. Cognitive anxiety decreased after the defensive exercise, hinting at a specific adaptation to that maneuver type. Overall, the findings suggest that despite the different tactical nature of each maneuver, both elicited similar psychophysiological responses that underline the need for targeted physical fitness and specialized training programs for fighter pilots.
Keskimölö et al., 2024 Association Between Cumulative G-force Exposure and Cervical Spine Degenerative Changes	Observational Study (Retrospective Cohort Study)	The study involved 56 male fighter pilot cadets from the Finnish Air Force, all aged 20 at the start of the study.	The pilots flew high-performance aircraft, specifically BAE Hawks, over a follow-up period of 5 years. During this time, their G-force exposure was measured using the Fatigue Index (FI), which records the number of times certain G-force levels are exceeded during flights.	The primary outcomes measured were degenerative changes in the cervical spine, assessed through MRI scans. Specific changes included intervertebral disc (IVD) degeneration and IVD herniations.	The study considered the cumulative G-force exposure as a key variable, measured by the FI. The average FI recorded was 1.98 (±0.47) over an average of 220 (±21) flight hours.	There was a statistically significant progression in the IVD degeneration sum score, although it did not correlate with FI values. A significant increase in the prevalence of IVD herniations was observed, with a negative correlation to FI values. This suggests that higher G-force exposure might not directly increase the risk of herniations, possibly due to avoidance behavior or other unmeasured factors. Other degenerative changes in the cervical spine did not show significant progression or correlation with FI values.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Chayrez et al., 2024 Performance Optimization and Injury Mitigation for Air Force Student Fighter Pilot	Observational Study (Retrospective Cohort Study)	The study involved Air Force student pilots (SPs) from Luke Air Force Base (AFB) and Eglin AFB. Participants included F-16 and F-35 student pilots actively enrolled in the Basic Course. A total of 198 SPs completed the Spine Training Program (STP), with 170 males and 12 females from Luke AFB, and 16 males from Eglin AFB.	The exercise protocol was an 8-week Spine Training Program (STP) designed to improve cervical endurance. The program was standardized and implemented at both Luke AFB and Eglin AFB. The Cervical Endurance Hold (CEH) test was used to measure performance before (intake) and after (exit) the STP.	The primary outcome measured was the change in Cervical Endurance Hold (CEH) performance from intake to exit. The study aimed to assess the effectiveness of the STP in improving CEH, independent of the location of administration.	Variables such as age, height, weight, % body fat, and fat-free mass were considered, but no significant differences were found between intake and exit at either base.	Significant improvements in CEH were observed across all groups, with a 33.6% increase overall from intake to exit. Specific subgroup improvements included a 20.4% increase for females from Luke AFB, a 34.5% increase for males from Luke AFB, and a 55.7% increase for males from Eglin AFB. The study concluded that the STP led to significant improvements in cervical endurance, with a large effect size, indicating meaningful changes regardless of training location. The study suggests the need for future randomized control trials to compare the STP with other spine training programs for better insights into optimal training methods for fighter aircrew.
Sung et al., 2024 Analysis of the relationship between body imbalance characteristics and physical ability in air force cadets: physical function and gravity acceleration resistance	Observational Study (Cross-Sectional Study)	The study involved 363 male cadets from the Korean Air Force Academy. These participants underwent various tests to assess their physical abilities and body imbalances.	The cadets were subjected to high-intensity physical activities, which are essential for withstanding gravitational acceleration. The study included functional movement screen tests, anatomical structure measurements, G-tests, and body composition and physical fitness tests.	The primary outcomes measured were the cadets' performance in the G-test, functional movement screen (FMS) scores, and the correlation between leg length and FMS scores. The G-test assessed the cadets' ability to withstand gravitational forces, while the FMS evaluated body asymmetry and functional movement.	The study considered variables such as bilateral imbalance in movements like active straight leg raises, deep squats, shoulder mobility, rotary stability, and functional leg length. These variables were analyzed to understand their impact on G-test performance and overall physical Ability.	The study found that high body balance positively affects gravitational acceleration resistance and exercise performance. Cadets who passed the G-test showed different patterns of bilateral imbalance compared to those who failed. Specifically, the pass group had significant differences in active straight leg raises, while the fail group showed differences in deep squats, shoulder mobility, and rotary stability. Leg length was significantly correlated with several FMS measurements, indicating that both functional and structural leg lengths are important for physical performance. The findings suggest that functional movement and physical imbalance significantly affect performance in activities involving gravitational acceleration, such as piloting and winter sports.

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Green & Ford, 2006 G-induced loss of consciousness: retrospective survey results from 2259 military aircrew	Observational Study (Retrospective Cohort Study)	The study surveyed 4018 Royal Air Force (RAF) aircrew members, regardless of their current role. Responses were received from 2259 individuals, which is a 56.2% response rate. Among the respondents, 882 (39%) were current fast jet aircrew	The survey did not specify a particular exercise protocol but focused on gathering data about G-LOC experiences, roles, aircraft types, and attitudes toward G-LOC prevention. The study aimed to reassess the prevalence of G-LOC with the introduction of the Typhoon aircraft and evaluate the effectiveness of current G tolerance training	The primary outcome measured was the prevalence of G-LOC among RAF aircrew. The survey also collected data on the circumstances of G-LOC events, such as the G-forces involved and the type of maneuvers being performed.	The study considered various contextual variables, including the type of aircraft, the aircrew's experience level, and the specific maneuvers associated with G-LOC events. It was noted that G-LOC was most commonly reported in aircrew under training and in training aircraft. The majority of G-LOC events occurred at G-forces between +5 to +5.9 Gz, and "push-pull" maneuvers were linked to 31.3% of these events	The prevalence of G-LOC among all respondents was 20.1%, with a 6% prevalence among fast jet aircrew. G-LOC was most prevalent in aircrew with less than 100 hours of total flying time. Despite the risks, 50.6% of respondents did not consider pulling G to be a problem, although over 80% acknowledged the importance of flying currency, anti-G suits, and physical fitness. A significant portion (55.6%) of respondents believed that centrifuge training would be beneficial. The study concluded that the prevalence of G-LOC has not significantly changed since 1987, indicating a need for continued education and training, especially with the introduction of new aircraft like the Typhoon

+Gz – Positive Gravitational Force along the head-to-foot axis; A-LOC – Almost Loss of Consciousness; AFB – Air Force Base; AGSM – Anti-G Straining Maneuver; BOS – Blood Oxygen Saturation; BMI – Body Mass Index; CEH – Cervical Endurance Hold; CSAI-2R – Competitive State Anxiety Inventory – 2 Revised; CSCS – Certified Strength and Conditioning Specialist; FMS – Functional Movement Screen; FI – Fatigue Index; G-LOC – G-induced Loss of Consciousness; GRIM – G-Risk Indicator Management Program; HR – Heart Rate; HRV – Heart Rate Variability; IHS – Isometric Hand Strength; IVD – Intervertebral Disc; MRI – Magnetic Resonance Imaging; NB – Normal Breathing; NIRS – Near-Infrared Spectroscopy; PPB – Positive Pressure Breathing; RAAF – Royal Australian Air Force; RAF – Royal Air Force; RMSSD – Root Mean Square of Successive Differences (HRV measure); rSO_2 – Regional Oxygen Saturation (cerebral); SPs – Student Pilots; SSP – Stress Subjective Perception; STAI – State-Trait Anxiety Inventory; STP – Spine Training Program; THUMS – Toyota Human Model for Safety; UPT – Undergraduate Pilot Training; WSO – Weapons Systems Officer

Appendix S11. Details of studies and information relevant to Assessment and Prediction of G-Tolerance

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Ohrui et al., 2024 G-Induced Loss of Consciousness Prediction Using a Support Vector Machine	Observational Study (Retrospective Cohort Study)	The study involved 124 flight course students as subjects. These individuals were likely chosen due to their relevance to the study's focus on fighter pilots and the risks they face with G-induced loss of consciousness (G-LOC).	The exercise protocol involved exposing subjects to high +Gz forces, which are typical in fighter jet maneuvers. The study aimed to predict G-LOC during the functional buffer period, which is the initial 5-6 seconds of high +Gz exposure where the brain can tolerate transient ischemia without losing consciousness.	The primary outcome measured was the prediction accuracy of G-LOC using different support vector machine (SVM) models. The study evaluated the performance of linear soft-margin SVM, nonlinear SVM with Gaussian kernel function (GSVM), and polynomial kernel function SVMs.	Several variables were considered in the SVM models, including age, height, weight, the use of anti-G suits, +Gz level, and cerebral oxyhemoglobin and deoxyhemoglobin concentrations. These factors were used as explanatory variables to predict G-LOC.	The study found that the GSVM model performed better than the other SVM models. The accuracy of the GSVM classifiers improved over time, reaching approximately 65% accuracy from 2.5 seconds after the onset of high +Gz exposure. This suggests that the GSVM model could potentially be used to predict G-LOC in real-time during flight or centrifuge training, although further analysis with more cases and factors is recommended to enhance accuracy.

Sharma., 2004 Assessment of Pulmonary and Cardiovascular Responses to Simulated Aerial Combat Maneuver	Doctoral Thesis (Dissertation for Doctor of Medicine in Aerospace Medicine)	The study focused on fighter aircrew volunteers who participated in the experiments voluntarily. Participants were actual aircrew members, meaning they were trained individuals who routinely experience high G environments during flight operations [2]. Their physical fitness and regular exposure to high acceleration environments make them an ideal group to study the responses of the human body under simulated combat conditions.	The exercise protocol involved a Simulated Aerial Combat Maneuver (SACM), which is designed to mimic the high acceleration conditions faced by fighter pilots during combat maneuvers. During SACM, subjects were exposed to high sustained G forces using a human centrifuge in a controlled setting at the Institute of Aerospace Medicine. The subjects were pushed until they reached a point of fatigue, which is measured by the duration for which they could tolerate the acceleration, termed as the G-duration tolerance. The protocol included monitoring the changes in lung function as well as the cardiovascular responses before and after exposure to high G forces.	Pulmonary Function Tests (PFTs): Key spirometric parameters were recorded, including Forced Vital Capacity (FVC), Forced Expiratory Volume in the first second (FEV1), FEV1/FVC ratio (FEV1%), Peak Expiratory Flow (PEF), as well as other flow rates and inspiratory capacities. These measurements help determine any changes or impairments in lung function due to exposure to high G forces. Cardiovascular Measurements: The study measured heart rate and systolic blood pressure, with a specific focus on the heart rate-systolic blood pressure product (double product), to estimate the myocardial oxygen demand during the maneuver. Recovery patterns of the heart rate and blood pressure post-exposure were also analyzed, providing insights into how quickly the cardiovascular system returns to normal after high-stress maneuvers. Additional Observations: While an attempt was made to record the recovery pattern in the ECG, technical modifications in the recording equipment limited this measurement.	The study considered the duration of acceleration (how long the subjects were exposed to the high G forces) as an important factor affecting both pulmonary and cardiovascular responses. Fatigue level was a determining variable, as the endpoint of the maneuver was reached when the subject felt too fatigued to continue. Other variables included individual differences in physiological responses, the use of G protective techniques, and pre- versus post-exposure comparisons to study recovery patterns.	The findings indicate that both the pulmonary and cardiovascular systems are significantly affected during SACM. Pulmonary function tests showed changes suggesting that exposure to high G forces can impair lung capacity or alter airway dynamics, which could be critical during operations requiring sustained performance. Cardiovascular responses, such as the increased heart rate and blood pressure, highlighted a notable strain on the heart during high acceleration. The double product increased during the maneuver, indicating a higher workload on the heart and correlating with the development of fatigue. Recovery patterns post-exposure demonstrated how quickly or slowly the heart rate and blood pressure returned to baseline, helping to understand the resilience of the cardiovascular system under such stressful conditions. Overall, the study provided vital data to possibly improve training protocols and protective measures for aircrew, ensuring better safety and performance in high G environments.

Tu et al., 2020 Combined effect of heart rate responses and the anti-G straining manoeuvre effectiveness on G tolerance in a human centrifuge.	Observational Study (Cross-Sectional Study)	The study involved fighter pilots who had completed intermediate high-G training. A total of 530 attempts from 436 subjects were analyzed. Most trainees were male, as female participants were excluded due to the small number of cases. The subjects were required to have a medical clearance before participating in the training	The high-G training involved four centrifuge profiles, with the 9G profile being the target. This profile required subjects to sustain 9G stress for 15 seconds. The training included a gradual onset rate (GOR) run to assess relaxed G tolerance (RGT) and straining G tolerance (SGT), and very high onset rate (VHOG) runs to practice the anti-G straining manoeuvre (AGSM) under different G stresses.	The primary outcome was the proportion of failed attempts to tolerate the 9G profile for 15 seconds. Heart rate (HR) responses and AGSM effectiveness were key variables measured. HR was monitored continuously, and the increase ratio was calculated during different phases of the 9G exposure.	Variables such as age, body mass index (BMI), RGT, SGT, and AGSM effectiveness were considered. These were retrieved from training documents and were used to assess their impact on the training outcomes.	Older age, lower BMI, poor AGSM effectiveness, and smaller HR increases were associated with a higher likelihood of failing the 9G profile. Good AGSM performance could mitigate the negative effects of a smaller HR increase on G tolerance. The study highlighted the importance of both HR responses and AGSM effectiveness in determining G tolerance, suggesting that effective AGSM can enhance cardiovascular function and improve G tolerance.
Whinnery & Forster, 2013 The +Gz-induced loss of consciousness curve.	Theoretical Article	The study involved completely healthy human subjects, including volunteer research subjects, aircrew undergoing training, students in aerospace medical disciplines, and aircrew undergoing medical evaluation. All participants had passed military physical examinations or equivalent health evaluation. The data comprised 888 G-LOC episodes from approximately 723 individuals, with some experiencing multiple episodes.	The study utilized data from centrifuge experiments where subjects were exposed to various +Gz profiles. These included gradual onset rate (GOR) profiles, rapid onset rate (ROR) profiles, simulated aerial combat maneuvering, and other complex experimental profiles. Subjects were in an upright sitting position and restrained with shoulder harness-lap belt systems during the exposures	The primary outcome measured was the time from the onset of +Gz stress to the onset of loss of consciousness (LOC), known as LOCINDTI. The study also measured the onset rate of acceleration and the maximum +Gz level reached during exposure	The study considered various acceleration profiles and the presence or absence of anti-G protection methods, such as anti-G suits and anti-G straining maneuvers. The data included a range of onset rates and +Gz levels, reflecting different types of acceleration stress.	Two G-LOC curves were developed, showing that for rapid onset rates (≥ 1.0 G/s), G-LOC occurs in a mean time of 9.10 seconds, independent of the onset rate. For rapid onset rate exposures to +Gz levels ≥ +7 Gz, G-LOC occurs in a mean time of 9.65 seconds. The minimum +Gz-level threshold tolerance was defined as +4.7 Gz. The study concluded that understanding the acceleration kinetics of loss and recovery of consciousness is crucial for medical diagnosis and aerospace operations.
Whinnery et al., 2014 The +Gz recovery of consciousness curve.	Theoretical Article	The study analyzed data from a centrifuge data repository, which included 760 episodes of recovery of consciousness (G-ROC) from healthy humans. These episodes were collected from centrifuge exposures at the USAF School of Aerospace Medicine and the Naval Air Warfare Center between 1978 and 1992.	The subjects were exposed to various +Gz profiles using operational type aircraft ejection seats. The protocol involved securing the subjects in an upright position with lap and shoulder restraints. The experiments were conducted to observe the loss and recovery of consciousness due to acceleration stress.	The primary outcome measured was the time from loss to recovery of consciousness, defined as the absolute incapacitation period (ABSINCAP). This was determined by observable signs of loss and recovery of consciousness, such as muscle tone and facial expression changes.	The study considered variables such as the offset rate of deceleration and the maximum +Gz level (GMAX) during exposure. The offset rate was found to be a significant factor influencing the duration of ABSINCAP, while GMAX was not directly predictive of recovery time.	The mean time for recovery of consciousness was 10.4 seconds, with a range from 1 to 38 seconds. A hyperbolic relationship was found between the offset rate and ABSINCAP, indicating that faster offset rates lead to quicker recovery of consciousness. The study concluded that while higher +Gz levels increase the duration of unconsciousness, the time for recovery is more dependent on the offset rate rather than the +Gz level itself

Burton, 1986 A conceptual model for predicting pilot group G tolerance for tactical fighter aircraft.	Doctoral Thesis	The paper does not explicitly detail the specific population characteristics, but it implies that the model is applicable to groups of tactical fighter pilots. The focus is on predicting group mean G tolerances, which suggests a consideration of average characteristics within this populations.	The paper does not describe a specific exercise protocol. Instead, it discusses various anti-G methods and physiological responses that can be used to enhance G tolerance. These include the use of an anti-G suit, reclined seating, anti-G straining maneuvers (AGSM), positive pressure breathing (PPB), gradual onset of G, isometric muscular contraction, and leg elevation.	The primary outcome measured is the group mean G tolerance, which is the ability of pilots to withstand gravitational forces. The model also predicts the amount of AGSM required, expressed in mm Hg, to achieve desired G tolerance levels. This effort is linked to fatigue and performance decrements, with a specific threshold of 50 mm Hg or an increase of 2 G in the upright seat being recommended for routine use.	The model considers several contextual variables related to anti-G methods and physiological responses. These include the type of anti-G suit, seat recline angle, the specific AGSM technique used, the application of PPB, the rate of G onset, and the use of isometric muscular contractions and leg elevation.	The model developed in the paper provides a static prediction of G tolerance based on the eye-heart vertical distance. It was validated with published data, indicating its reliability. The derived equation for AGSM effort offers a practical tool for assessing fatigue and performance impacts on pilots. The recommendation of a maximum AGSM of 50 mm Hg or a 2 G increase in the upright seat is a significant finding for operational guidelines in fighter Aviation.
Whinnery & Forster, 2017 The first sign of loss of consciousness.	Theoretical Article	The study involved 212 instances of unconsciousness episodes (UNCEs) selected from a larger repository of data from 888 healthy humans. These participants included fighter aircrew, flight surgeons, and experimental subjects, indicating a mix of individuals with backgrounds in military aviation and research settings. The participants were rigorously examined and qualified through complete military flying physical examinations, ensuring that they were fit for centrifuge exposure and accelerated stress experiments.	The method used to induce UNCEs involved applying head-to-foot acceleration stress (+Gz-stress) using human centrifuges. This mimicked conditions similar to those experienced during aerial combat. Two distinct acceleration profiles were employed: the gradual onset rate (GOR) and the rapid onset rate (ROR). GOR exposures were characterized by a continuously linear ramp with lower onset rates (<1 G/s), while ROR exposures featured a more abrupt, nearly linear ramp to plateau with higher onset rates (≥1 G/s). During the exposures, subjects maintained a focused upward gaze on a central light which facilitated monitoring of visual field loss. This element was part of the standard procedure for aborting the acceleration run if signs of impending unconsciousness were noticed.	The study measured the onset and sequence of motor and ocular signs corresponding to the loss of consciousness (LOC) phase. The first sign was determined by detailed video analysis of the subjects and was used as a marker for the onset of the LOC phase. Parameters such as the loss of motor control (M), eyelid closure (L), eye fixation (F), upward eye deviation (U), and muscular twitching (T) were recorded. Special attention was given to the sign complex ML (loss of motor control and eyelid closure) which occurred in the majority (53.3%) of cases. The duration of the unconscious phase, or the absolute incapacitation period (ABSINCAP), was measured from the first sign of LOC until the first sign of the recovery phase (ROC).	Key contextual variables included the type of acceleration exposure (GOR vs. ROR), which impacted components like the magnitude and rate of the +Gz-stress and the corresponding physiological response times (e.g., LOC induction time). The study also considered the role of cerebral perfusion measured indirectly by the critical head-level arterial blood pressure (cHdABP). This variable helped explain the occurrence of the neurological signs once a specific perfusion threshold was passed.	The initial sign of LOC was most frequently due to a loss of motor control, with the ML sign complex observed as the dominant initial response in both GOR and ROR profiles. Despite the differences in acceleration onset times (with ROR inducing faster LOC induction compared to GOR), the ultimate sequence and type of neurological signs were similar, suggesting that both protocols induced the same type of cerebral ischemia in the cephalic nervous system. The study emphasized the importance of accurately identifying the initial sign of LOC, as it serves as a crucial starting point for detailed kinetic analyses of unconsciousness episodes, which can later aid in differential diagnosis and refining experimental protocols.

Choi et al., 2015 Detection of G-Induced Loss of Consciousness (G-LOC) prognosis through EMG monitoring on gastrocnemius muscle in flight.	Observational Study (Cross-Sectional Study)	The study involved pilots and pilot trainees from the Korean Air Force. Participants were subjected to high G-force training using a human centrifugal simulator to simulate flight conditions that could lead to G-LOC.	Participants performed the Anti-G Straining Maneuver (AGSM), which includes L-1 respiration maneuvering and muscular contraction of the whole body. The focus was on monitoring the Electromyogram (EMG) of the gastrocnemius muscle, which is actively engaged during AGSM.	The primary outcomes measured were the integrated absolute value (IAV) and waveform length (WL) of the EMG signals. These metrics reflect muscle contraction and fatigue, and their rapid decay was observed during the alarm phase, 3 seconds before G-LOC.	The study was conducted under controlled conditions using a human centrifugal simulator to replicate the high G-force environment experienced by fighter pilots. The focus was on the physiological response of the gastrocnemius muscle during AGSM under these conditions.	A significant finding was the rapid decay of IAV and WL values during the alarm phase, indicating an impending G-LOC. The study developed an algorithm to detect G-LOC prognosis by monitoring these EMG features, which can generate warning signals in real-time. The system enhances the accuracy of detecting G-LOC by analyzing the decay trend and degree of IAV and WL values when pilots initiate AGSM during sudden acceleration above 6G.
Rudnjanin et al., 2006 Loss of consciousness as criterion of +Gz tolerance at Institute of Aviation Medicine MMA during +Gz acceleration selective test.	Observational Study (Cross-Sectional Study)	The study examined 2,192 candidates over a period of 20 years. These candidates were assessed for their tolerance to +Gz acceleration, which is critical for aircrews flying high-performance fighter aircraft.	The primary method used was the "Test of Linear Increasing of Acceleration" (TOLIA). The test involved a gradual onset rate (GOR) of 0.1 G/s. Maximum/peak values of +5.5 Gz, +6.0 Gz, and +7.0 Gz were applied, depending on the candidate's intended role (e.g., Air Academy, supersonic combat aircraft training, or high-performance combat aircraft).	The main outcomes measured were loss of peripheral vision, extreme pulse rate (above 180 bpm.), arrhythmias, and loss of consciousness (G-LOC). G-LOC was considered the most critical endpoint, leading to immediate disqualification from flying duties.	The study was conducted using a centrifuge to simulate +Gz acceleration. The selection criteria varied based on the intended flying duties of the candidates, with different peak Gz values applied accordingly.	Out of 2,192 candidates, 11 experienced G-LOC episodes, accounting for 0.50% of the subjects. G-LOC episodes occurred without warning symptoms such as loss of peripheral vision, gray out, or blackout. Nine G-LOC episodes occurred during primary selection (+5.5 Gz), one during secondary selection (+6.0 Gz), and one during tertiary selection (+7.0 Gz). G-LOC was the only endpoint that resulted in permanent disqualification, whereas other endpoints allowed for retesting after a minimum of seven days.

Ryoo et al., 2004 Consciousness monitoring using near-infrared spectroscopy (NIRS) during high +Gz exposures.	Experimental Study (Controlled, Non-Randomized)	The study involved nine human volunteers, including eight males and one female. The average male subject was around 31 years old, with a height of about 176 cm and a weight of approximately 79 kg. The female volunteer was 34 years old, about 162.6 cm tall, and weighed around 61 kg. Participants were carefully selected and consent was obtained in agreement with U.S. Navy and Department of Health and Human Services guidelines. The small and specific group indicates that the study was performed under controlled conditions with healthy individuals to observe the effects of +Gz stress on consciousness.	The study used a dynamic flight simulator (DFS) that mimicked high acceleration forces similar to those that pilots experience in high-performance aircraft. Two distinct +Gz exposure profiles were applied: Sustained +Gz plateaus: Participants were exposed to rapid onset of acceleration that increased from +1.25 to +6, +8, or +10 Gz and maintained for 15 seconds or until loss of consciousness occurred. Repeated short duration +Gz pulses: These were brief bursts starting at 0.25 seconds and gradually increasing in duration until the subjects experienced visual or consciousness impairment symptoms. The acceleration profiles were designed to study both immediate and cumulative effects of acceleration stress on brain oxygenation and consciousness.	The primary outcome measured was the relative cerebral oxygen saturation (rSO_2), which is a non-invasive measure of oxygen levels in the brain tissue. Other outcomes included: The onset of almost loss of consciousness (A-LOC) and actual loss of consciousness (G-LOC). These were observed along with the associated symptoms during the exposures. Incapacitation time (ICAP): This measured the length of time the subjects remained unconscious until they could respond to a cue, providing a measure of recovery time after G-LOC. The study also assessed changes in the concentrations of hemoglobin and deoxygenated hemoglobin using near-infrared spectroscopy (NIRS) to correlate with changes in rSO_2 during the acceleration profiles.	The acceleration levels were critical variables, with exposures at +6, +8, and +10 Gz being compared to assess differences in physiological response. The type of profile (sustained plateau vs. repeated pulses) served as another key variable that influenced the degree of rSO_2 drop and the ICAP. It was also noted that the duration of exposure below a critical rSO2 level impacted the length of incapacitation, indicating that not just the intensity but also the time factor played an important role in G-LOC events.	The study demonstrated that once the rSO_2 dropped to a specific threshold, subjects experienced loss of consciousness (G-LOC), and this threshold effect was repeatable regardless of the +Gz level or duration. Findings indicated that repeated short duration +Gz pulses produced a greater drop in rSO2 and shorter ICAP compared to sustained +Gz exposures, which produced smaller rSO_2 drops but longer recovery times. The relationship between rSO_2 and pulse width was linear across the different acceleration levels, highlighting that both the magnitude and duration of the drop in cerebral oxygenation are crucial in determining the onset and recovery from consciousness loss. Overall, the study provides important data for developing control systems in protective gear for pilots, arranging the response based on both oxygen saturation levels and the duration below critical thresholds.
Kim et al., 2017 G-LOC Warning Algorithms Based on EMG Features of the Gastrocnemius Muscle.	Observational Study (Cross-Sectional Study)	The study involved 67 participants, comprising pilots and pilot trainees from the Korean Air Force. These individuals were subjected to high-G training using a human centrifugal simulator to simulate the conditions that could lead to G-induced loss of consciousness (G-LOC).	The exercise protocol involved high-G training on a human centrifugal simulator. This setup was used to simulate the sudden acceleration in the +Gz axis, which is known to cause G-LOC by affecting the oxygenated blood supply to the brain.	The primary outcomes measured were the electromyogram (EMG) features of the gastrocnemius muscle. Seven specific EMG features were analyzed: root mean square (RMS), integrated absolute value (IAV), mean absolute value (MAV), slope sign changes (SSC), waveform length (WL), zero crossing (ZC), and median frequency (MF). These features were used to assess muscle contraction and fatigue.	The study focused on the decay trends of specific EMG features, particularly IAV and WL, which showed rapid decay before the onset of G-LOC. These trends were used to develop algorithms for detecting G-LOC during flight.	The study successfully developed two algorithms based on the EMG features of the gastrocnemius muscle. These algorithms were able to detect G-LOC with a sensitivity of 100% and a specificity of 66.7%. The algorithms monitored the decay trends of IAV and WL to predict the probability of G-LOC occurrence, providing a potential real-time countermeasure for pilots.

Onozawa et al., 2008 A new evaluation method for +Gz tolerance with loratadine by using a near-infrared spectroscopy.	RCT (Randomized Controlled Trial)	The study involved nine healthy volunteer subjects, consisting of eight males and one female, with a mean age of 34.3 years. All participants were experienced centrifuge riders and were not on any medication. They were prohibited from consuming caffeine and smoking on the day of the experiment.	The study used a double-blind, placebo-controlled, randomized, crossover protocol. Each subject received either a 10 mg loratadine capsule or a placebo 90 minutes before the centrifuge experiments. The centrifuge exposure included a gradual onset run (GOR) and a rapid onset run (ROR) to determine +Gz tolerance, which was defined by the visual endpoint or loss of consciousness (GLOC).	The primary outcomes measured were +Gz level tolerance, G-duration tolerance, and changes in cerebral NIRS variables (hemoglobin concentration changes and tissue oxygenation index). These were assessed to determine the effect of loratadine on +Gz tolerance.	The study was conducted under controlled conditions at the JASDF Aeromedical Laboratory. The subjects did not wear anti-G suits but performed voluntary G protective maneuvers. The NIRS system was used to measure cerebral hemodynamics during +Gz exposure.	The study found no significant differences in +Gz tolerance between subjects taking loratadine and those taking a placebo. This was consistent across +Gz level, duration time, and NIRS variables. The results suggest that loratadine does not affect +Gz tolerance, supporting its safe use by aircrew without adverse effects on acceleration tolerance,
Chiang et al., 2021 A Cardiac Force Index Applied to the G Tolerance Test and Surveillance among Male Military Aircrew.	Observational Study (Prospective Study)	Participants: 92 male military aircrew Age: Mean 26.2 years (range: 22–47) Recruited from: Air Force Academy & National Defense Medical Center (Taiwan) Experience: No prior high-G training	Ground Stage: Use of wearable BioHarness 3.0 to record: Resting cardiac data (sitting) Walking data (3-minute walk) Centrifuge Stage: G tolerance tested using a human centrifuge at APRL Relaxed G Tolerance (RGT) and Straining G Tolerance (SGT) measured AGSM (Anti-G Straining Maneuver) taught and practiced	Primary: RGT (Relaxed G Tolerance) SGT (Straining G Tolerance) Cardiac Parameters: Resting Cardiac Force Index (RCFI) Walking Cardiac Force Index (WCFI) Cardiac Force Ratio (CFR = WCFI/RCFI) Physiological Measures: HR, SBP, DBP	Anthropometrics (height, weight, BMI) Lifestyle (smoking, drinking, exercise habits) Use of anti-G suit (not inflated during test) Centrifuge parameters (0.1 G/s onset rate, max 9G	WCFI positively correlated with both RGT and SGT Each 100-unit increase in WCFI: ↑ RGT by 0.14 G ↑ SGT by 0.17 G Exercise habits were linked to improved RGT Taller participants had lower G tolerance WCFI is a useful non-invasive predictor of G tolerance and may help in surveillance programs.
Kuo et al., 2023 G Tolerance Prediction Model Using Mobile Device-Measured Cardiac Force Index for Military Aircrew: Observational Study.	Observational Study (Longitudinal Study)	Participants: 213 military aircrew trainees Age: Mean 25.6 years Gender: 13.1% female Location: Aviation Physiology Research Laboratory (APRL), Taiwan Inclusion: Underwent high-G centrifuge training between Jan 2020–Dec 2022	Devices: BioHarness 3.0 wearable sensor to track heart rate and activity Phases: Ground testing: cardiac data at rest and while walking Centrifuge testing: G tolerance under slowly increasing G load (0.1 G/s) G Measures: RGT (Relaxed G Tolerance) SGT (Straining G Tolerance)	Physiological: Heart rate, systolic/diastolic blood pressure Cardiac Force Index (CFI) Walking CFI (WCFI), Resting CFI (RCFI), Cardiac Force Ratio (CFR) Performance: RGT and SGT values in centrifuge Predictive models for G tolerance using WCFI and other variables	Demographics: age, height, weight, gender Physiological: SBP, HR Lifestyle: exercise, alcohol, and smoking habits AGSM execution and anti-G suit use	WCFI was a strong positive predictor of both RGT and SGT Higher systolic BP and lower resting HR correlated with better G tolerance Taller individuals had slightly lower G tolerance Developed prediction equations for estimating G tolerance using WCFI and other physiological factors Suggests real-time mobile monitoring of cardiac performance can help predict and manage G tolerance in pilots.

Choi et al., 2010 Ultrasonographic finding of internal jugular vein during anti-G straining maneuver: is it associated with gravity-induced loss of consciousness	Observational Study (Cross-Sectional Study)	The study involved 47 male trainee pilots with a mean age of 23.9 years. These participants were part of a human centrifuge education program and were not familiar with anti-gravity straining maneuver (AGSM) skills.	The exercise protocol included ultrasonographic monitoring of the internal jugular vein during AGSM, followed by human centrifuge training. The centrifuge protocol involved a maximum of 6G with a sustaining time of 30 seconds. The centrifuge training was used to simulate high G-force conditions to assess the effectiveness of AGSM in preventing gravity-induced loss of consciousness (G-LOC).	The primary outcomes measured were the shape and size of the internal jugular vein during AGSM, specifically looking for a concave contour and the cross-sectional area. The occurrence of G-LOC during centrifuge training was also recorded.	Variables such as well-being sensation, smoking, drinking, sleeping, height, and weight were collected through questionnaires. These were considered as potential factors influencing G-LOC.	The study found that a concave contour and a smaller cross-sectional area of the internal jugular vein during AGSM were associated with a higher likelihood of G-LOC. Specifically, the presence of a concave portion along the vein's contour had an adjusted odds ratio of 9.00 for G-LOC, and for every cm^2 decrease in the cross-sectional area, the odds ratio was 3.10.
Scott et al., 2013 Subjective and objective measures of relaxed +Gz tolerance following repeated +Gz exposure	Experimental Study Controlled (Non-Randomized)	The study involved 10 healthy male volunteers. Participants were experienced centrifuge volunteers, familiar with the measurement of relaxed +Gz tolerance (RGT). The average age of participants was 28 years, with a mean weight of 83.9 kg and height of 1.79 meters.	Participants underwent repeated exposure to +Gz acceleration on a man-rated centrifuge. The protocol included two experimental conditions: exposure either twice or four times per week for three consecutive weeks. Each session involved four simulated air combat maneuvers (SACM), with each maneuver consisting of cycles at different +Gz levels.	The primary outcome was relaxed +Gz tolerance (RGT), measured during a gradual onset run (GOR). Cardiovascular responses, such as heart rate and blood pressure, were assessed during rapid and incremental head-up tilt tests.	The study considered the frequency of +Gz exposure as a variable, comparing two sessions per week against four sessions per week. The use of anti-G equipment, such as full-coverage anti-G trousers, was part of the protocol to simulate real flight conditions.	Repeated +Gz exposure improved cardiovascular tolerance to orthostatic stress, as indicated by increased mean arterial pressure and diastolic blood pressure during tilt tests. Despite these cardiovascular adaptations, there was no improvement in subjective RGT, meaning the threshold of +Gz that participants could tolerate without losing visual cues did not increase. The study suggests that while the body adapts to handle the stress better, it does not necessarily enhance the ability to withstand higher +Gz levels.
Park et al., 2016 Physical Condition Does Not Affect Gravity-Induced Loss of Consciousness during Human Centrifuge Training in Well-Experienced Young Aviators	Observational Study (Cross-Sectional Study)	The study focused on young male aviators from the Republic of Korea Air Force (ROKAF) who were on active flight duty. These aviators had experience flying high-performance aircraft for at least two years. A total of 361 aviators met the inclusion criteria, but only 350 had complete data and were included in the study	The aviators underwent human centrifuge training, which is a mandatory part of their military training to maintain their pilot's license. The centrifuge training involved rapid onset +Gz exposures, starting from +1.2G to +9G, maintained for 15 seconds. During the training, a pneumatic anti-G suit was used, and the aviators performed anti-G straining maneuvers (AGSM).	The study measured various physical condition parameters, including body composition, physical fitness level (such as muscle power and cardiopulmonary endurance), and pulmonary function. The occurrence of gravity-induced loss of consciousness (G-LOC) during the centrifuge training was the primary outcome measured.	The study considered factors like the aviators' basic characteristics, body composition, and physical fitness levels. These were measured using bioimpedance spectroscopy and other fitness tests. The study also took into account the use of anti-G suits and AGSM during the centrifuge training.	There was no significant difference in physical conditions, such as muscle mass, strength, and general endurance, between aviators who experienced G-LOC and those who did not. The study concluded that physical condition does not appear to be a significant determinant of G-LOC among well-experienced aviators. The authors suggested that factors like coordination and adaptation to effective timing during AGSM might be more important for G-tolerance than physical condition alone.

Sovelius et al., 2022 +Gz Exposure and Flight Duty Limitations.	Observational Study (Retrospective Cohort Study)	The study focused on a population of fighter pilots who began their jet training between 1995 and 2015. The primary endpoint for this population was the imposition of permanent flight duty restrictions due to spinal Disorders.	The study did not specifically outline an exercise protocol. Instead, it analyzed the cumulative +Gz exposure experienced by pilots during their sorties. This exposure was quantified using a fatigue index (FI), which records the number of times certain levels of +Gz are exceeded during flights.	The main outcome measured was the rate of permanent flight duty restrictions due to spinal disorders. The study found an annual dropout rate of 0.86% among the fighter pilot population due to these spinal issues.	Several potential confounding factors were considered, including flight hours, periods of intensive flying, fitness test results, and nicotine product use. However, no statistical differences were found between pilots with permanent flying restrictions and their matched controls in these areas.	The study did not identify a specific breaking point or individual factor responsible for Gz-induced spinal disorders. The results highlighted the multifactorial nature of the problem, suggesting that a combination of factors contributes to spinal health issues in fighter pilots. Consequently, the study recommends multifactorial countermeasures to protect pilots' Health.
Shin, 2023 Association of Genotype, High-G Tolerance, and Body Composition in Jet Aircraft Aviators	Observational Study (Cross-Sectional Study)	The study involved 81 Korean F15 and F16 pilots. Participants were aged between 25-39 years.	The pilots underwent human centrifuge testing at +8.5 Gz, which is considered a high-intensity exercise. Exercise tolerance was assessed by measuring the mean breathing interval during these high-g tests.	The primary outcomes measured were the genotypes of the ACTN3 and ACE genes. High-g tolerance was evaluated based on the pilots' performance in the centrifuge tests. Body composition parameters such as height, body weight, muscle mass, body mass index, body fat percentage, and basal metabolic rate were also measured.	The study focused on the correlation between genetic factors (ACTN3 and ACE genotypes) and high-g tolerance. Body composition was considered to see if it had any correlation with the genotypes and high-g tolerance.	The ACTN3 RR genotype showed a significant correlation with +8.5 Gz tolerance. Pilots with the DI genotype of the ACE gene exhibited the highest high-g tolerance, although the DD genotype had a higher test pass rate in preliminary studies. No significant correlation was found between body composition parameters and the genotypes. The study suggests a potential plural gene effect on high-g tolerance, indicating that both ACTN3 and ACE genes may play a role in determining high-g tolerance in pilots.
Kumar, 2023 +Gz Standards for the Indian Air Force	Doctoral Thesis	The study analyzed data from aircrew who participated in the Operational Training in Aerospace Medicine for Fighters course at the Institute of Aerospace Medicine, Indian Air Force (IAF). The timeframe for the data collection was from January 2017 to December 2020. A total of 334 aircrew members were included in the study.	The training involved assessing the aircrew's ability to tolerate high-G forces, which is crucial for fighter pilots. The protocol included gradual onset rate tolerance tests to determine the aircrew's ability to withstand G-forces without experiencing G-induced loss of consciousness (G-LOC).	The primary outcome measured was the aircrew's G-tolerance, specifically their ability to avoid G-LOC during high-G stress. The study also measured the failure rate of aircrew in achieving the training goals, which was found to be less than 1%.	The study considered the difference in G-tolerance between aircrew who experienced G-LOC and those who did not during training. The odds of experiencing G-LOC at 9 G after clearing the 7-G and 8-G profiles were also evaluated, with odds ratios of 4.4 and 4.7, respectively.	The study concluded that aircrew with higher G-tolerance have a reduced chance of experiencing G-LOC. The existing high-G training program at the IAF has been effective and aligns with the operational training goals of the organization. The study suggests the need for an operational definition of G-tolerance that aligns with the training objectives of the IAF.

Whinnery, 1982 G-tolerance enhancement: straining ability comparison of aircrewmen, non-aircrewmen, and trained centrifuge subjects	Experimental Study (Controlled, Non-Randomized)	The study involved three groups: aircrewmen, non-aircrewmen, and trained centrifuge subjects. These groups were assessed at the USAF School of Aerospace Medicine over a period of three years.	The exercise protocol included G tolerance measurements both in a relaxed state and while using a protective straining maneuver. The focus was on comparing the ability to perform these maneuvers among the different groups.	The primary outcome measured was the G tolerance of the participants. This included both relaxed G tolerance and the improvement in G tolerance when using a protective straining maneuver.	The study considered the level of training and experience of the participants, particularly distinguishing between currently trained pilots and fully trained centrifuge panel members. The timing of G training, specifically during undergraduate pilot training, was also considered as a variable that could influence outcomes.	Currently trained pilots, including those flying fighter-type aircraft, were found to be less proficient in performing G protective straining maneuvers compared to fully trained centrifuge panel members. With adequate training, pilots could potentially increase their G tolerance by at least 2 Gs over their relaxed G tolerance. The study suggests that the optimal time for G training is during undergraduate pilot training, indicating that early and focused training could enhance G tolerance capabilities.
Bacevic et al., 2024 Heart Rate Variability as a Predictor of +Gz Tolerance During the High-G Selective Test	Observational Study (Cross-Sectional Study)	The study involved 36 pilot candidates who were subjected to centrifuge tests to assess their +Gz tolerance. These candidates were part of a preselection process for military pilots, which is crucial for determining their suitability for high-G environment.	The exercise protocol consisted of centrifuge runs with specific +Gz-acceleration phases. The protocol included a 2-G plateau, an increase to 5.5 G, a decrease back to 2 G, and ended with another plateau. This protocol was designed to simulate the stress conditions pilots might experience during flight.	The primary outcome measured was heart rate variability (HRV), specifically time-domain HRV indices such as the standard deviation of the normal-to-normal interval (SDNN) and the root mean square of successive differences. These indices were calculated for both a 60-second 2-G plateau and the entire test Duration.	The study considered various endpoints used by the Aero Medical Institute in Belgrade, such as peripheral vision loss, heart rate exceeding 180 bpm, cardiac arrhythmias, and G-induced loss of consciousness, to assess relaxed +Gz tolerance. These factors were crucial in determining the candidates' cardiovascular adaptability to stress.	The study found that candidates who met the criteria for +Gz tolerance (Group 1) had significantly higher HRV indices compared to those who did not meet the criteria (Group 2). Specifically, Group 1 had higher mean SDNN values during both the 2-G plateau and the entire test. This suggests that higher HRV is positively correlated with better +Gz tolerance, indicating that HRV can be a useful predictor and selection tool for military aircrew.
Van Lieshout et al., 1992 Assessment of cardiovascular reflexes is of limited value in predicting maximal +Gz-tolerance	Observational Study (Cross-Sectional Study)	The study involved 10 healthy subjects. The specific demographics such as age, gender, or other health conditions are not detailed in the provided context.	The subjects underwent tests involving continuous Finapres blood pressure (BP) and heart rate (HR) monitoring. These tests included the Valsalva maneuver, standing, and forced respiratory sinus arrhythmia to assess cardiovascular reflexes.	The primary outcome measured was the correlation between cardiovascular responses to the tests and +Gz-tolerance. Specifically, the study looked at G-levels of peripheral light loss (PLL) during centrifuge runs at a rate of 0.1 G/s.	The study focused on the integrity of neural cardiovascular reflex control as a potential determinant of +Gz-tolerance. The cardiovascular findings were within normal ranges, indicating no autonomic dysfunction among the subjects.	The study found that only the mean BP recovery during the Valsalva maneuver showed a marginally significant correlation with PLL ($r = 0.63$, $p = 0.049$). The results suggest that while intact neural cardiovascular control is necessary for tolerating +Gz-stress, it does not determine maximal +Gz-tolerance. The assessment of cardiovascular reflexes may confirm baroreflex integrity but has limited value in predicting +Gz-tolerance.

Lan et al., 2023 High G Tolerance and Cardiopulmonary Reserve Function in Healthy Air Force Aviators	Observational Study (Cross-Sectional Study)	The study involved 264 male fighter aviators, each with more than 500 hours of flight experience. The average age, height, weight, and body mass index (BMI) were similar between those who experienced G-LOC/A-LOC and those who did not.	Participants underwent cardiopulmonary exercise testing (CPET) and human centrifuge testing to assess their cardiopulmonary reserve function (CPRF) and G tolerance.	The study measured forced vital capacity (FVC), forced expiratory volume in 1 second (FEV1), and the ratio of FEV1 to FVC (FEV1/FVC) as part of pulmonary function tests. CPET-related parameters such as oxygen uptake, exercise blood pressure, and oxygen pulse were also evaluated.	The study focused on the relationship between cardiopulmonary reserve and the risk of gravity-induced loss of consciousness (G-LOC) or almost loss of consciousness (A-LOC).	14% of the aviators experienced G-LOC/A-LOC during the human centrifuge test. There were no significant differences in CPET-related parameters between the G-LOC/A-LOC group and the non-G-LOC/A-LOC group. The FEV1/FVC ratio was significantly lower in the G-LOC/A-LOC group, suggesting that slightly lower ventilation might increase the likelihood of experiencing G-LOC/A-LOC. Other factors such as oxygen uptake and exercise blood pressure were not found to be significant influences of G-LOC/A-LOC.
Shin et al., 2022 Associations between ACE Genotypes, +8.5 Gz Tolerance, and Body Composition in F-15 Pilot Candidates	Observational Study (Cross-Sectional Study)	N = 20 Korean F-15 pilot candidates Age: 23.0–28.6 years All required to pass a +8.5 Gz tolerance test Genotyped for ACE (Angiotensin-Converting Enzyme) gene polymorphism (DD, DI, II)	+8.5 Gz test for 15 seconds in a high-speed human centrifuge Performance assessed using mean breathing intervals Body composition (muscle mass, fat %, BMI) measured using InBody 720 Genetic material collected after testing for ACE genotyping	Primary: Pass/fail status in +8.5 Gz test Mean breathing interval during test Body composition metrics (weight, muscle mass, BMI, body fat %, BMR) Secondary: Association of ACE genotype with test outcomes and physical characteristics	ACE genotype (DD, DI, II) Previous centrifuge training history Ethnic homogeneity of participants	Pass Rate by Genotype: DD: 75% DI: 66.7% II: 30% (DD > II, $p < .05$) Body Composition: DD genotype showed higher body weight, muscle mass, BMI, and BMR Conclusion: +Gz tolerance may be associated with ACE genotype Suggests DD genotype may provide better physiological advantage under high-G stress Recommends further large-scale studies to confirm genetic impact
Dosel et al., 2004 Testing method of plus and minus Gz tolerance at Czech Air Force pilots.	Observational Study (Cross-Sectional Study	The study focused on Czech Air Force pilots. These individuals are trained professionals who operate combat aircraft and are subject to various gravitational forces during flight maneuvers.	The exercise involved real flight conditions where pilots experienced alternating plus and minus Gz forces. The flights were conducted at two different altitudes: a safe altitude of 7000 feet and a low-level flight at 900 feet above ground. This setup was used to evaluate the pilots' physiological responses to these conditions.	The primary outcomes measured were continuous blood pressure and heart rate. These physiological parameters were monitored to assess the pilots' tolerance to the gravitational forces experienced during the flights.	The study considered the altitude at which the flights were conducted as a significant variable. The difference in altitude (7000 ft vs. 900 ft) was used to compare the physiological responses of the pilots under varying conditions of gravitational stress.	The study concluded that a high level of tolerance to plus and minus Gz forces is essential for pilots, especially during low-level flights in agile aircraft. It was demonstrated that using a sinusoidal profile during real flights is a viable method for evaluating pilots' tolerance to these forces. Additionally, a system was developed for acquiring physiological signals in the cockpit of combat aircraft, which facilitated the study-

Stevenson & Scott, 2014 +Gz tolerance, with and without muscle tensing, following loss of anti-G trouser pressure	RCT (Randomized Controlled Trial)	The study involved 10 healthy, male, nonsmoking subjects. Participants were experienced with high +Gz acceleration and familiar with the use of anti-G trousers (AGT). The mean age was 32 years, with a standard deviation of 6 years. The average height was 1.78 meters, and the average body mass was 85 kg	Subjects underwent two visits to a centrifuge facility, experiencing different +Gz exposure conditions. In Visit 1, subjects were relaxed, while in Visit 2, they tensed their lower body muscles. Each visit included +Gz exposures with AGT deflation after 5 and 30 seconds, both relaxed and with muscle tensing. Muscle tensing was employed to see if it increased +Gz tolerance following AGT deflation.	The study measured the maximum +Gz level tolerated before central light loss (CLL). Visual symptoms, eye-level systolic blood pressure (SBP eye), and mean blood flow velocity in the middle cerebral artery (MCAV mean) were recorded. The time from AGT deflation to the onset of visual symptoms and to CLL was also measured.	The study considered the effects of muscle tensing and +Gz exposure duration on +Gz tolerance. The impact of AGT deflation on visual symptoms and blood pressure was analyzed.	Muscle tensing increased +Gz tolerance by approximately 0.5 G, independent of exposure duration. The time to first visual symptoms was shorter with 5 seconds of +Gz exposure compared to 30 seconds. Muscle tensing resulted in a quicker progression from first symptoms to CLL compared to relaxed conditions. The study found that +Gz tolerance following AGT deflation was comparable to that without inflation, with muscle tensing providing a modest increase in tolerance.
Park et al., 2016 Effects of the optimal flexor/extensor ratio on G-tolerance.	Observational Study (Cross-Sectional Study)	The study involved Korean Air Force students, with a sample size of 77 participants. The body composition of these students was measured using an impedance method.	A muscular function test was conducted using a Humac Norm device at angular speeds of 60°/sec and 240°/sec. Additionally, an isokinetic muscular function test was performed to assess the participants' muscle strength and endurance.	The study measured several outcomes, including muscle mass, fat percentage, BMI, knee flexion peak torque, and total work of knee extension. The flexor/extensor ratio of the trunk and knees was also evaluated to determine its impact on G-tolerance	The study considered variables such as muscle mass, fat percentage, and BMI, which were found to be significantly higher in the failed C and passing groups compared to the failed A group. These variables were crucial in understanding the differences in G-tolerance among the groups.	The passing group exhibited a significantly higher left knee 60°/sec flexion peak torque compared to the failed B group. The total work of left knee extension was significantly higher in the failed C and passing groups than in the failed A group. A higher trunk flexor/extensor ratio was observed in the C group and the passing group compared to the failed A group. The study concluded that balancing the right and left knee flexor/extensor ratio and having a high trunk flexor/extensor ratio are essential for enduring high G-tolerance tests. Additionally, improving maximum muscular strength is necessary to cope with rapidly increasing acceleration.

A-LOC – Almost Loss of Consciousness; ABSINCAP – Absolute Incapacitation Period; ACE – Angiotensin-Converting Enzyme; AGSM – Anti-G Straining Maneuver; AGT – Anti-G Trousers; AFB – Air Force Base; BMR – Basal Metabolic Rate; BMI – Body Mass Index; CFI – Cardiac Force Index; CLL – Central Light Loss; CPET – Cardiopulmonary Exercise Testing; CPRF – Cardiopulmonary Reserve Function; CFR – Cardiac Force Ratio; CSCS – Certified Strength and Conditioning Specialist; DBP – Diastolic Blood Pressure; ECG – Electrocardiogram; EMG – Electromyogram; FEV1 – Forced Expiratory Volume in 1 Second; FMS – Functional Movement Screen; FVC – Forced Vital Capacity; GOR – Gradual Onset Run; GSVM – Gaussian Kernel Support Vector Machine; G-LOC – G-induced Loss of Consciousness; HR – Heart Rate; HRV – Heart Rate Variability; ICAP – Incapacitation Time; IAV – Integrated Absolute Value (EMG metric); IVD – Intervertebral Disc; MCAV mean – Mean Blood Flow Velocity in the Middle Cerebral Artery; MF – Median Frequency (EMG metric); MMA – Military Medical Academy; MRI – Magnetic Resonance Imaging; NB – Normal Breathing; NIRS – Near-Infrared Spectroscopy; PBG – Pressure Breathing during G; PFT – Pulmonary Function Test; PLL – Peripheral Light Loss; PPB – Positive Pressure Breathing; PSA – Power Spectrum Area; RCT – Randomized Controlled Trial; RGT – Relaxed G Tolerance; ROC – Recovery of Consciousness; ROR – Rapid Onset Run; rSO2 – Regional (Cerebral) Oxygen Saturation; SBP – Systolic Blood Pressure; SBP eye – Eye-Level Systolic Blood Pressure; SGT – Straining G Tolerance; SSC – Slope Sign Changes (EMG metric); STP – Spine Training Program; SVM – Support Vector Machine; THUMS – Toyota Human Model for Safety; TOLIA – Test of Linear Increasing of Acceleration; UNCE – Unconsciousness Episode; WL – Waveform Length (EMG metric); WCFI – Walking Cardiac Force Index; ZC – Zero Crossing (EMG metric)

Appendix S12. Details of studies and information relevant to External Factors Affecting G-Tolerance

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Levkovsky et al., 2018 Aviator's Fluid Balance During Military Flight	Observational Study (Retrospective Cohort Study)	The study involved 48 aviators from the Israeli Air Force. The mean age of the participants was 23.9 years. The study included 104 training flights across various flight platforms.	The study focused on military flight as the exercise protocol. Bodyweight and urine specific gravity were measured before and after each flight to assess fluid balance. Environmental heat strain was also measured to understand its impact on fluid loss.	The primary outcome measured was fluid loss, calculated as the difference in bodyweight before and after the flight. The rate of fluid loss was also determined, with a mean fluid loss rate of 462 ml per hour. The study analyzed the effect of different variables, such as aircraft type and flight duration, on fluid loss using univariate and one-way ANOVA.	Different aircraft platforms were considered, including Blackhawk helicopters and fighter jets. Flight duration varied, with Blackhawk flights averaging 108 minutes and fighter jet flights averaging 35.5 minutes.	Blackhawk pilots experienced the highest total fluid loss per flight due to longer flight durations. Fighter jet pilots had the highest rate of fluid loss per hour, with rates reaching up to 692 ml per hour when extrapolated. In 11% of the flights, aircrew completed their missions with a significant fluid loss, indicating a potential risk to flight safety due to dehydration.
Khomenko, Bukhtiarov, & Malashchuk, 2003 Effects of extended flight factors on +Gz tolerance	Observational Study (pre-post design)	N = 6 test subjects (likely single-seat fighter pilots or trained military personnel). All had known baseline tolerance to +Gz, from earlier pre-experimental data. Healthy individuals suitable for centrifuge testing.	Subjects underwent 5-hour flight simulation (long-duration mission-like conditions) Followed by centrifuge exposures: Gradual +Gz exposure (0.1 G/s rate), using muscle relaxation only and no anti-G suit Complex profile exposure (2.0 to 9.0 Gz at 1.0 G/s), with AGS-3 suit and anti-G straining maneuvers (AGSM) Baseline (control) tolerance values from prior testing were used for comparison.	+Gz tolerance (thresholds for visual symptoms, G-LOC risk) Visual disturbances and cardiac arrhythmias Hemodynamic parameters (likely HR, BP) during and post-centrifugation. External respiration and gas exchange parameters post-exposure. Leg muscular effort and cervical muscle fatigue during runs.	5-hour simulation duration as a fatigue/stress model Use vs. non-use of AGS and AGSM Comparison to subject-specific baseline values.	Extended flight simulation (5 hours) decreased +Gz tolerance Increased incidence and severity of visual disturbances and cardiac arrhythmias Higher energy expenditure and cervical muscle fatigue observed The study emphasizes the physiological cost of long-duration missions and the need for preventive strategies to sustain G-tolerance.
Zeigler & Acevedo, 2024 Re-evaluating the Need for Routine Maximal Aerobic Capacity Testing within Fighter Pilots	Systematic Review	The study focuses on Air Force fighter pilots. However, specific demographic details such as age, gender, or number of participants are not provided in the context. The emphasis is on the general population of fighter pilots and their performance under G-load conditions.	The paper reviews existing research rather than conducting new experiments, so it does not specify a particular exercise protocol. It discusses the role of aerobic training in enhancing maximal aerobic capacity (Vo2 max) and its impact on G-tolerance.	The primary outcome measured is the maximal aerobic capacity (VO2 max) and its relationship to G-tolerance. The study examines how VO2 max testing can predict G-induced loss of consciousness and assess performance in anti-G straining maneuvers and heart rate variable during increased G-load.	The study considers variables related to human performance, exercise physiology, and the specific demands of fighter pilot maneuvers. It also addresses the belief that aerobic training might negatively impact arterial pressure response and G-tolerance.	The review concludes that increasing V˙o2V˙o2 max through aerobic training does not hinder G-tolerance. It suggests that routine V˙o2V˙o2 max testing could be beneficial in air force protocols to enhance readiness, reduce health risks, and improve training for fighter pilots. The study supports the integration of V˙o2V˙o2 max testing to provide insights into fitness, risks, and tailored exercise plans for pilots

Study	Study Design	Population Characteristics	Exercise Protocol	Outcomes Measured	Contextual Variables	Key findings
Jeong et al., 2024 Relationship between sleep quality and gravitational tolerance	Observational Study (Cross-Sectional Study)	157 male cadets from the Republic of Korea Air Force Academy Classified into: G-tolerance test pass group (n = 87) G-tolerance test fail group (n = 70)	Participants underwent a G-tolerance test on a high-speed centrifuge: Target: 5 G for 30 seconds Used L-1 breathing technique Pre-test instruction by experienced trainers Also performed: Physical fitness test (3 km run, push-ups, sit-ups) Body composition analysis (InBody 720) Completed Pittsburgh Sleep Quality Index (PSQI) questionnaire.	Primary: G-tolerance test duration (seconds) Secondary: PSQI global and domain scores Physical performance: running time, push-ups, sit-ups Body composition: muscle mass, fat %, BMI	Sleep quality (PSQI score <5 vs. ≥5). Physical fitness and body composition. All participants lived under similar training and environmental conditions.	Better sleep quality (PSQI <5) was associated with 4.7 times higher odds of passing the G-tolerance test. Negative correlation between PSQI score and G-tolerance test time (i.e., worse sleep = lower tolerance). No significant differences in fitness or body composition between pass/fail groups. Emphasized that sleep quality—not just quantity—may be crucial for G-tolerance in aviators.

AGS – Anti-G Suit; AGSM – Anti-G Straining Maneuver; ANOVA – Analysis of Variance; BMI – Body Mass Index; BP – Blood Pressure; CEH – Cervical Endurance Hold; CLL – Central Light Loss; CPET – Cardiopulmonary Exercise Testing; CFR – Cardiac Force Ratio; FEV1 – Forced Expiratory Volume in 1 Second; FI – Fatigue Index; FVC – Forced Vital Capacity; GOR – Gradual Onset Run; G-LOC – G-Induced Loss of Consciousness; HR – Heart Rate; HRV – Heart Rate Variability; ICAP – Incapacitation Time; IAV – Integrated Absolute Value; MCAV – Middle Cerebral Artery Blood Flow Velocity; MF – Median Frequency; MAV – Mean Absolute Value; NIRS – Near-Infrared Spectroscopy; PEF – Peak Expiratory Flow; PLL – Peripheral Light Loss; PSQI – Pittsburgh Sleep Quality Index; RCT – Randomized Controlled Trial; RCFI – Resting Cardiac Force Index; RGT – Relaxed G Tolerance; ROR – Rapid Onset Run; SBP – Systolic Blood Pressure; SGT – Straining G Tolerance; SSC – Slope Sign Changes; VO_2 Max – Maximal Oxygen Uptake; WL – Waveform Length; WCFI – Walking Cardiac Force Index; ZC – Zero Crossing