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G-Force Tolerance in Fighter Pilots: A Scoping Review With Evidence Gap Map

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ABSTRACT

Background: Despite growing interest in G-force tolerance, the literature remains fragmented, lacking an integrated synthesis that encompasses physiological, cognitive, training, and equipment-related dimensions. Fighter pilots are frequently exposed to high +Gz environments, which can compromise vision, cardiovascular stability, and consciousness. Understanding G-tolerance is vital for flight safety, operational readiness, and the long-term health of aircrew.

Objective: This scoping review aims to map the existing evidence on G-force tolerance in fighter pilots and identify key physiological, anthropometric, cognitive, and operational factors. It also seeks to explore enhancement strategies and assess underrepresented populations, with the goal of guiding future research and improving pilot safety and performance.

Methods: The review followed the JBI methodology and adhered to the PRISMA-ScR guidelines. Searches were conducted across eight databases and grey literature, including studies published up to March 31, 2025. A total of 118 studies met the inclusion criteria, encompassing a range of study designs and international contexts.

Results: Findings revealed eight key themes: assessment and prediction of G-tolerance, physical conditioning, physiological and anthropometric factors, training and prevention strategies, equipment and technology, physiological effects of high-G exposure, risks and impacts, and external influences. Although AGSM proficiency, cardiovascular reflexes, and muscular strength were consistently associated with improved tolerance, substantial gaps were found in gender representation, longitudinal tracking, and integration of real-time physiological monitoring technologies.

Conclusion: This review highlights the multifactorial nature of G-force tolerance and underscores the need for personalized, interdisciplinary approaches in pilot training and assessment. It provides a comprehensive foundation for future research aimed at optimizing high-G performance, with recommendations for standardized protocols, inclusive study populations, and expanded use of wearable monitoring tools.

Keywords: Aerospace physiology; Anti-G straining maneuver (AGSM); Cardiovascular physiology; High-performance aviation; Pilot training

INTRODUCTION

Fighter pilots operating high-performance aircraft are routinely subjected to high gravitational acceleration forces (+Gz) (1, 2), which can impair vision, compromise cardiovascular function (3), and yield G-induced loss of consciousness (G-LOC) (4). G-force tolerance, the ability to endure such forces without significant physiological or cognitive impairment—is a critical determinant of flight safety and operational capability in military aviation environments (5-7). The demand for sustained high-G maneuvers in modern air combat makes understanding the multidimensional factors that influence G-tolerance increasingly vital for optimizing pilot performance, training, and long-term health outcomes (3, 8).

Despite a substantial and growing body of literature on G-tolerance, existing research presents considerable variability in methodology, focus, and population. Studies have examined cardiovascular reflexes (9-11), muscle function (12), cognitive load (13), and genetic markers (14), but findings are often fragmented and lack comprehensive synthesis. Additionally, significant gaps remain, including limited representation of female pilots (15, 16), scarce longitudinal tracking of pilot adaptation or injury (17-19), and insufficient real-time physiological monitoring during flight operations (20, 21). Strategies such as the Anti-G Straining Maneuver have been explored in this context, yet these approaches are rarely examined as part of integrated models (22).

A scoping review is the most appropriate method to address this complex and interdisciplinary field. Unlike systematic reviews, which aim to answer narrowly focused questions, scoping reviews are designed to map the existing body of literature across broad topics, identify key concepts, and highlight knowledge gaps (23). This approach is particularly relevant in the context of aviation physiology, where the interactions between physical conditioning, equipment ergonomics, and neurocognitive performance require holistic exploration. This review aims to systematically identify and categorize the existing literature on G-force tolerance in fighter pilots, synthesize findings across physiological, cognitive, training, and equipment-related domains, assess the methodological rigor and scope of current research, and identify gaps and provide recommendations for future investigation. The following questions guide this review: what physiological, biomechanical, and cognitive factors influence G-tolerance in fighter pilots; what strategies and technologies have been used to enhance G-tolerance; what populations and contexts have been underrepresented in current literature; and how have assessment methods and training protocols evolved over time.

Existing studies emphasize that heart rate variability (HRV), baroreflex sensitivity, and the effectiveness of anti-G straining maneuvers (AGSM) are key determinants of G-tolerance (9, 20, 24, 25). Muscle strength, particularly in the lower limbs, and high-intensity interval training have also been associated with improved performance under G-stress (12, 26). Moreover, advances in wearable technologies such as cardiac force index (CFI) and near-infrared spectroscopy (NIRS) show promise in predicting and monitoring G-tolerance in real-time (27, 28).

Given the complexity of G-force tolerance, this scoping review extends beyond previous fragmented investigations by integrating physiological, cognitive, physical, and equipment-related dimensions into a comprehensive framework. It emphasizes the need for standardized measurement protocols and interdisciplinary collaboration to overcome the inconsistencies found across studies. Focused specifically on military fighter pilots exposed to sustained high-G environments (e.g., F-16, F-15, Eurofighter), this review synthesizes data from operational missions and controlled environments such as centrifuge training and simulators. Through this mapping, the review not only highlights current evidence but also identifies underexplored domains, such as real-time physiological monitoring, sex-specific performance data, and ergonomic design considerations, guiding the development of future interventions to enhance flight safety and human performance.

METHODS

Protocol and Registration

This scoping review was reported according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist (29) and was registered with the Open Science Framework (registration: https://osf.io/52tbj) (30) under the identification code DOI 10.17605/OSF.IO/XC7RD.

Eligibility Criteria

This scoping review follows the Population, Concept, Context (PCC) framework (31). The Population includes F-16 pilots or comparable fighter pilots in high-G environments. The Concept focuses on strategies to enhance G-force tolerance, such as physical conditioning, AGSM, equipment design, and psychological techniques. The Context covers military aviation, training simulators, and operational environments. Eligible studies include RCTs, observational studies, simulations, military reports, and grey literature. Exclusions apply to studies on civilian pilots, astronauts, parachutists, animal models, computational simulations, microgravity research, aviation accidents, cockpit ergonomics, and non-military settings (e.g., motorsports, amusement rides). Studies without flight relevance, single case reports, non-systematic reviews, non-English papers without translation, and low-quality research will also be excluded.

Information sources and search

A systematic search of electronic databases (PubMed, Scopus, Web of Science all databases, SPORTDiscus, Air University Library Index to Military Periodicals, JSTOR Security Studies Collection, Military & Government Collection, and Military Database) was conducted for studies published up to March 31, 2025. Additional searches included grey literature, conference proceedings, and reference lists of selected articles. The search strategy incorporated relevant keywords related to fighter pilots, G-force tolerance, physiological adaptation, AGSM, equipment design, and cognitive performance. All identified studies were screened for relevance, and outcome variables were categorized into key themes to facilitate data synthesis and interpretation. The references were imported into a reference software manager (EndNote X9 ®; Thomson Reuters, Philadelphia, PA, United States), and the duplicate documents were excluded. The search strategies applied in other data- bases can be found in Supplementary Appendix S2.

Selection of source of evidence

The selection of studies was performed in two phases by two independent reviewers [JB and RMB]. In phase-1, titles and abstracts were screened based on the eligibility criteria (32). Disagreements were resolved through discussion or, if necessary, by consulting an additional reviewer [HS] (33). Next, in phase-2, studies that could not be excluded in the previous step underwent full-text analysis to determine eligibility, using the online software Rayyan® (Qatar Computing Research Institute, Qatar).

Data charting process

Following the screening of articles and data extraction, the authors analyzed the overarching themes and key topics related to G-force tolerance in fighter pilots. A standardized data extraction sheet was developed to systematically capture relevant study details, including study design, population characteristics, G-force tolerance interventions (such as AGSM training, physical conditioning, and equipment use), physiological and cognitive outcome measures (such as sustained G-tolerance, cardiovascular responses, and cognitive function), and key findings and conclusions. The collected data were inserted in a form previously prepared using Microsoft® Excel 16.29.1 (Microsoft Office 2019, Microsoft, Redmond, United States). The extracted data were synthesized to identify common trends, gaps in the literature, and potential areas for future research on optimizing pilot performance and safety in high-G environments (34).

Data Items

Outcomes from each study were categorized into overarching themes following established methodologies in previous research. The primary focus areas of this review included G-performance in female pilots, physiological and anthropometric factors related to G-tolerance, and the physiological effects of high-G exposure. Additionally, training and prevention strategies to enhance G-tolerance, physical conditioning and exercise for pilots, and advancements in equipment and technology were analyzed. The review also examined the risks and impacts of high-G environments on pilots, methods for assessing and predicting G-tolerance, and external factors influencing G-tolerance. Studies that reported outcomes spanning multiple categories were included in several tables to facilitate direct comparisons. However, studies that only assessed participant characteristics, such as pilot experience or flight hours, without directly linking them to G-force tolerance outcomes, were excluded from thematic tables and sections.

The extracted data included participant demographics (age, gender, pilot experience, and exposure to high-G environments), intervention details (type of G-force tolerance strategies used, including AGSM training, physical conditioning, psychological techniques, and equipment adaptations), outcome measures (physiological markers such as blood pressure and heart rate variability, performance metrics such as sustained G tolerance and reaction time, and subjective measures such as fatigue and mental workload), and contextual factors (G-force exposure levels, training environments, and flight hours per week).

To ensure consistency across studies, data were standardized where appropriate, such as converting units of measurement. As the primary aim of this scoping review is to map the extent, range, and nature of the literature on G-force tolerance in fighter pilots, no formal statistical analysis was performed. Instead, key study characteristics, outcomes, and findings were summarized to provide a comprehensive synthesis of existing knowledge in the field (35).

Critical appraisal of individual sources of evidence and Synthesis of results

Two independent reviewers [JB and RMB] extracted the data, resolving discrepancies by consensus [HS]. Key variables included participant demographics (age, gender, pilot experience, and G-force exposure), intervention details (AGSM training, physical conditioning, psychological techniques, and equipment adaptations), and outcomes (physiological markers, performance metrics, and subjective measures). Contextual data, such as training environments (simulator vs. real flight) and flight hours per week, were also collected. Extracted data were categorized into physiological adaptations, cognitive performance, training interventions, and equipment effectiveness, with findings summarized descriptively. No meta-analysis was conducted.

RESULTS

Selection of sources of evidence

A literature search initially identified 207 records. After removing 140 duplicates, 67 unique records remained for screening, of which 24 were excluded. This left 43 full-text reports assessed for eligibility. A total of 24 studies were excluded based on predefined eligibility criteria. The main reasons included case reports (n=4), lack of focus on military or fighter pilots (n=3), unrelated medical topics (e.g., dental, ophthalmologic, general neurocognitive) (n=3), and studies using simulations or animal models (n=2). Others were excluded

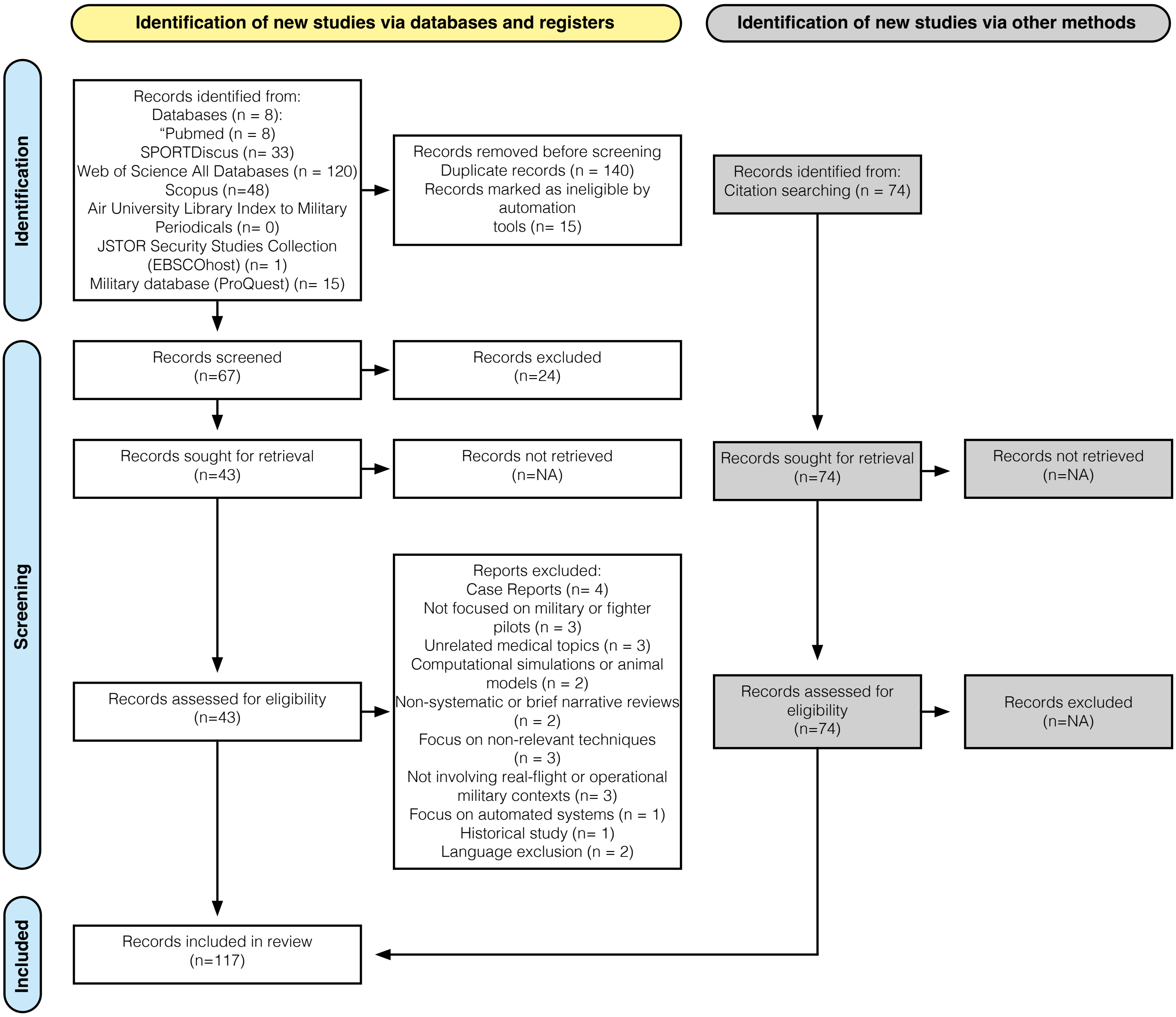

Figure 1. PRISMA Flow Diagram.

for being outdated, non-systematic reviews, or focusing on unrelated areas like Qigong, hypoxia, or supplements. Studies not involving real-flight military contexts or centered on automated systems rather than human tolerance were also excluded. These criteria ensured relevance and quality of included studies. Additionally, 74 records were identified through citation searching, all of which were assessed and included. In total, 117 studies were reviewed. The article selection process is shown in Figure 1. Supplementary Appendix S3 displays references of excluded articles alongside reasons for exclusion.

Characteristics of sources of evidence and Results of individual sources of evidence

Critical appraisal within sources of evidence

Out of a total of 117 studies on G-tolerance in fighter pilots, the most common focus was on the assessment and prediction of G-tolerance (30 studies, 26%), followed by research on physical conditioning and exercise for pilots (21 studies, 18%) and the risks and impacts of the high-G environment on pilots (16 studies, 14%). Studies on physiological and anthropometric factors influencing G-force tolerance (14 studies, 12%) and the physiological effects of high-G exposure (14 studies, 12%) were also significant. Research on training and prevention strategies to enhance G-tolerance accounted for 9 studies (8%). Investigations into equipment and technology for enhancing G-tolerance (7 studies, 6%), external factors affecting G-tolerance (4 studies, 3%), and the performance of female pilots in high-G environments (2 studies, 2%) were less frequent. This distribution highlights the strong emphasis on evaluating and improving G-tolerance, as well as the critical role of physical and physiological readiness for pilots operating in high-acceleration flight environments.

Synthesis of results

Publication Year and G-Tolerance Studies

Figure 2 illustrates the evolution of the number of publications over the years. From 1980 to 1989, there were 11 publications. This number increased during the 1990s, with 18 publications, and continued to rise in the 2000s, reaching 22 publications. The most significant growth occurred between 2010 and 2020, with 39 publications. In the most recent period, from 2021 to 2025, 27 publications were recorded. This upward trend reflects the growing interest and production of knowledge in the field over the decades.

Geography of Studies

Figure 3 presents the geographical distribution of the 118 studies on G-tolerance. The United States of America leads significantly with 23 publications, accounting for approximately 19% of the total (5, 6, 36-56), South Korea follows with 18 studies (15%) (14, 20, 57-72) while both the United Kingdom (24, 73-82) and Sweden (12, 83-92) contributed 11 studies each (9%). Other notable contributors include Finland with 8 studies (17, 93-99) and China (15, 100-105) with 7 publications, Japan with 7 (106-112), and Brazil with 6 (113-118). Taiwan (5 studies) (9, 27, 119-121), Turkey (13, 122, 123) and India (124-126), and Israel (127-129) (3 each) also show moderate participation. Additionally, several countries contributed a single study each, including Serbia (130), the Czech Republic (131), the Netherlands (132), Croatia (133), Germany (26), Spain (134), Poland (135), Norway (136), Greece (137), France (138), and Ukraine (139). This distribution highlights a strong research interest concentrated in a few countries, particularly the USA and South Korea, while also indicating a wide but limited global engagement across Europe, Asia, and the Americas.

Characteristics of sources of evidence and Results of individual sources of evidence

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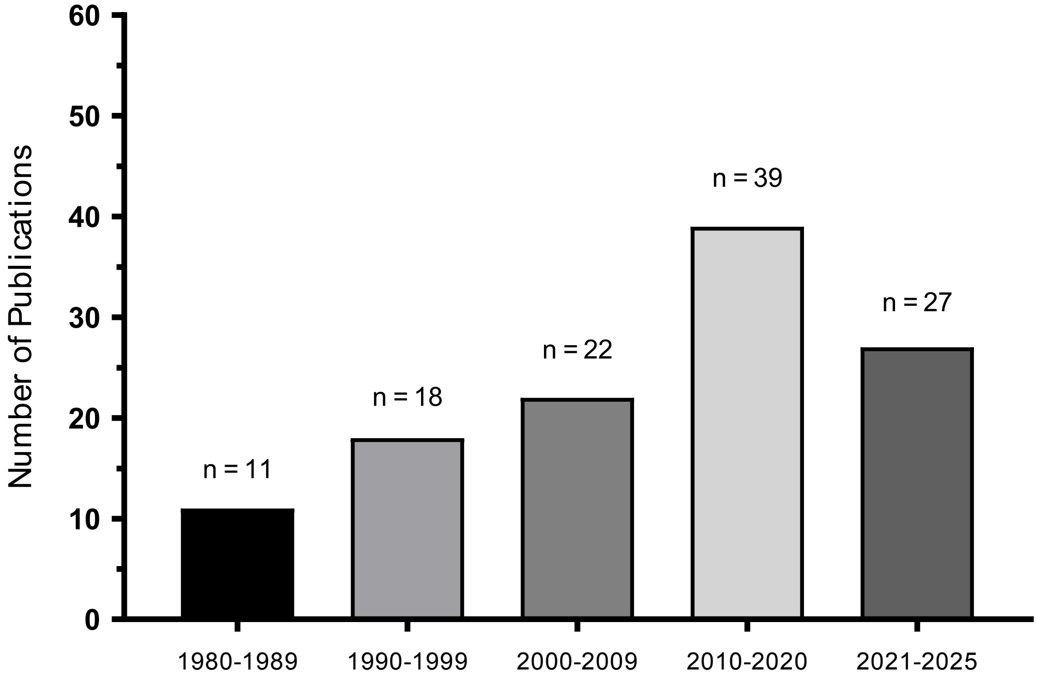

Figure 2. Number of publications by year.

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Synthesis of results

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Evidence Gap Map

Analysis of the EGM reveals several key findings: (1) there is a marked concentration of small-scale studies (with fewer than 30 participants), while longitudinal or large-cohort studies are scarce, and few investigate sustained adaptation to G-tolerance over time; (2) the vast majority of studies were conducted with male participants, with very few including women and even fewer performing sex-specific analyses or considering physiological and ergonomic differences; (3) training-focused studies—especially on AGSM protocols and centrifuge use—make up a significant portion of the literature, while cognitive and psychological dimensions of G-tolerance remain underexplored; (4) physiological outcomes such as heart rate variability and cerebral oxygenation are widely assessed, whereas long-term cardiovascular, cognitive, and neuropsychological effects receive limited attention; (5) equipment-centered interventions, such as anti-G suits and pressure

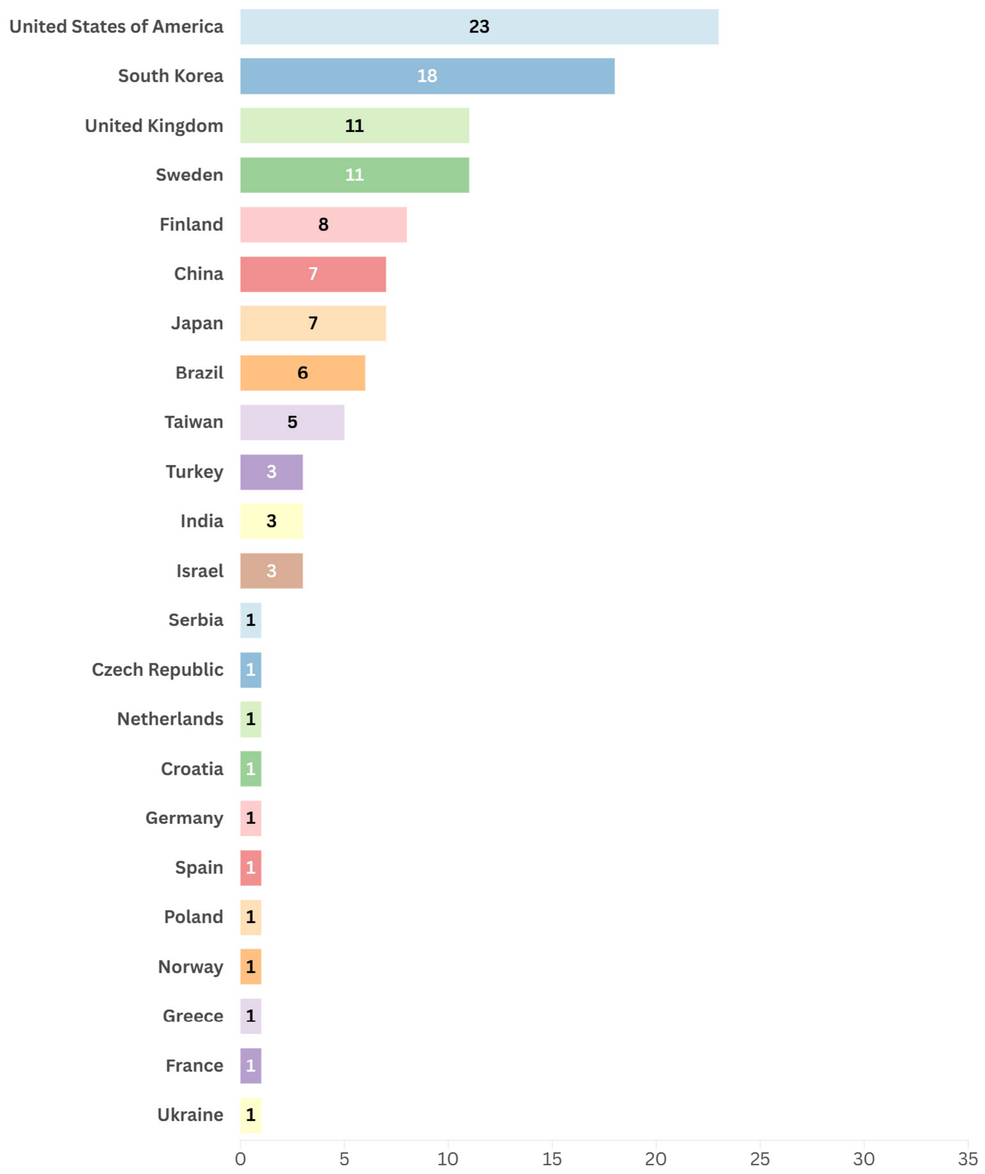

Figure 3. Number of publications by country.

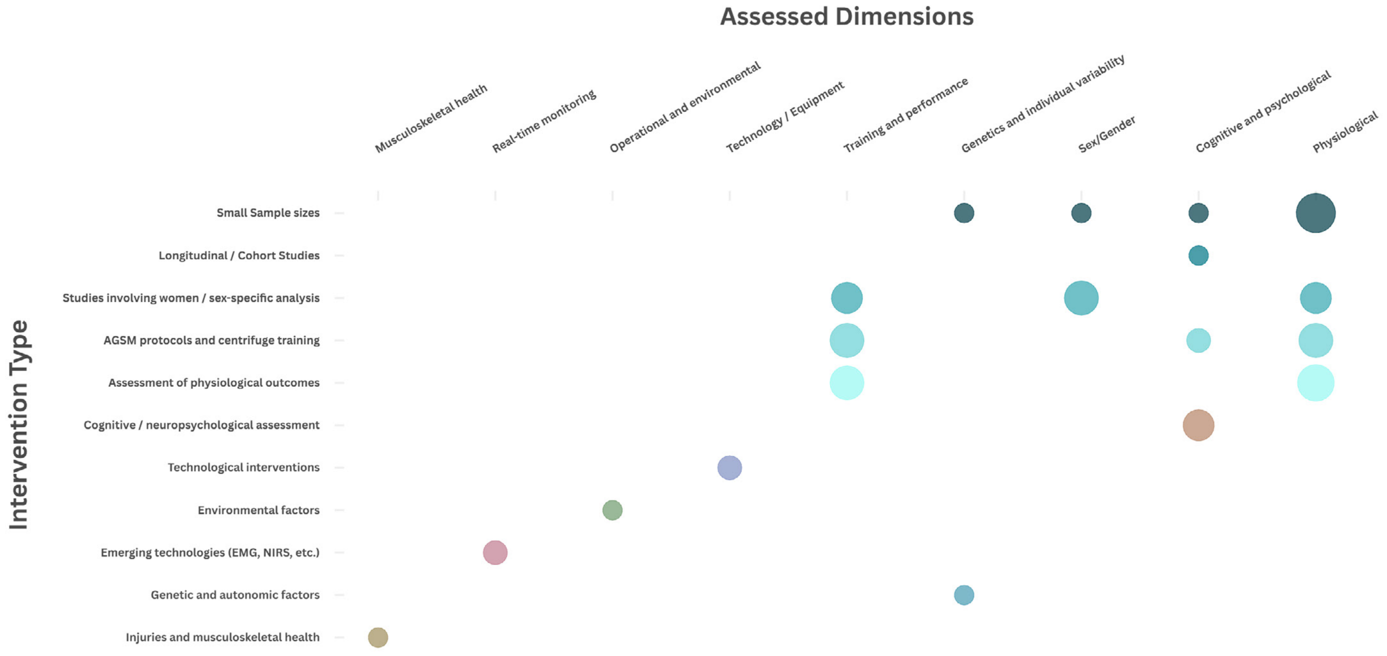

Figure 4. Evidence Gap Map about G-Force tolerance in fighter pilots.

breathing systems, are moderately represented, but research on comfort, usability, or integration with modern cockpit systems is limited; (6) environmental and operational stressors such as dehydration, sleep deprivation, and thermal load are mentioned in only a few studies, despite their critical relevance in mission contexts; (7) emerging real-time monitoring technologies, such as wearable EMG and near-infrared spectroscopy (NIRS), show promise but are rarely applied in operational flight environments, limiting their practical application; (8) psychological resilience and mental fatigue, although recognized as operationally important, are rarely addressed in the literature and are nearly absent in intervention-based studies; (9) genetic and autonomic predictors of individual variability in G-tolerance represent a promising area, but studies remain scarce, often lacking replication and sample diversity; and (10) injury prevention and long-term musculoskeletal health—particularly in relation to repeated G-force exposure—are underrepresented in intervention research, despite being recurring concerns among pilot populations.

As illustrated in Figure 4, the distribution of study themes reveals an uneven focus across key domains of G-tolerance research. Physiological and training-related factors dominate the literature, while cognitive, ergonomic, and gender-specific variables remain significantly underrepresented. This thematic imbalance highlights the need for standardized methodologies, broader inclusion of underrepresented populations such as female pilots, and interdisciplinary research approaches that combine physiological, cognitive, ergonomic, and operational aspects of performance in high-acceleration environments.

DISCUSSION

The aims of this scoping review were to (1) conduct a comprehensive and systematic search of the available literature on G-force tolerance in fighter pilots; (2) categorize and summarize the main outcomes and variables investigated in studies addressing G-force tolerance; (3) describe the methodological and contextual characteristics of

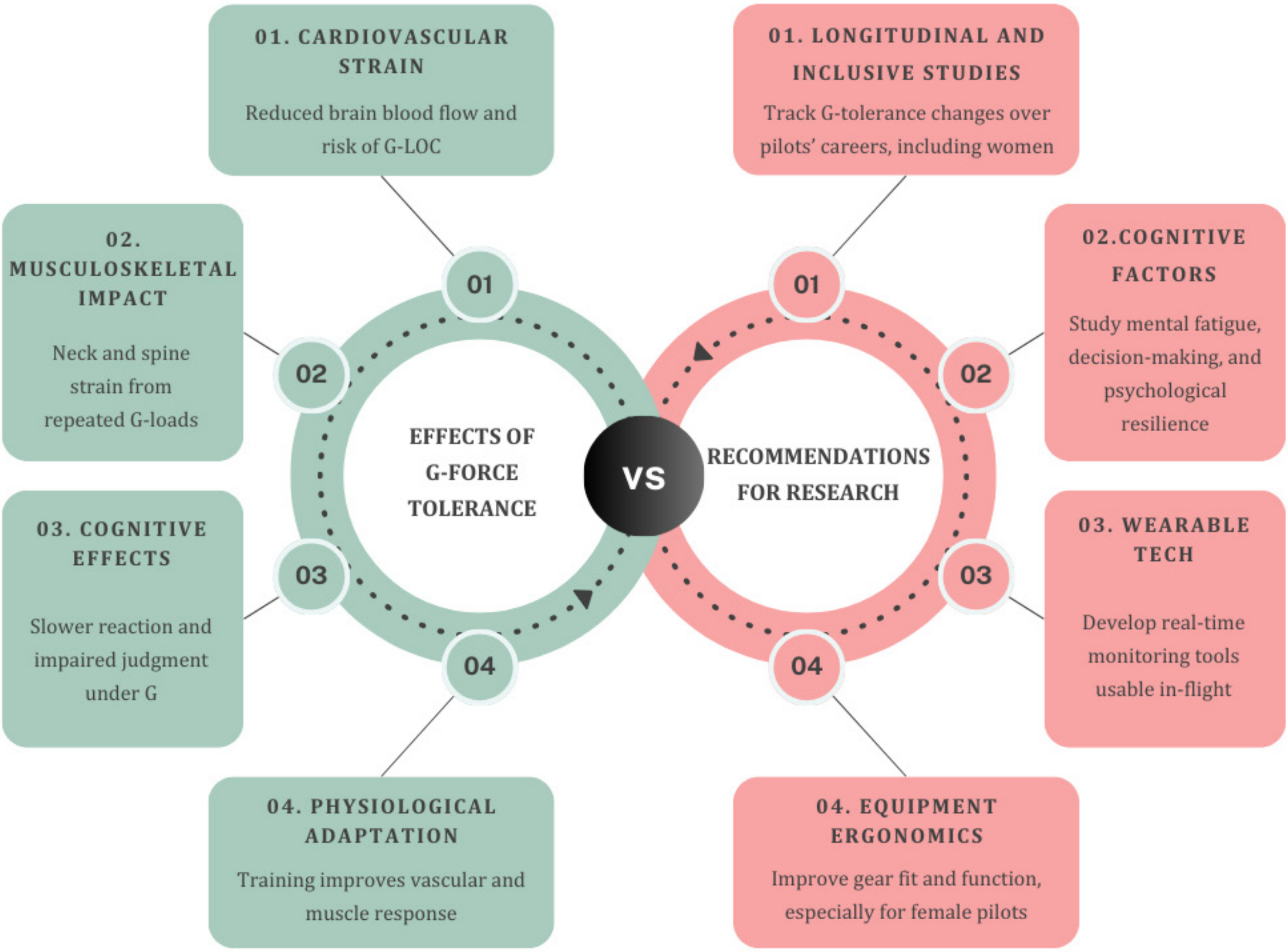

Figure 5. Effects of G-Force tolerance and future recommendations.

the included studies, highlighting patterns and geographical trends; and (4) identify knowledge gaps and provide recommendations to inform future research focused on enhancing pilot performance and safety in high-G environments. From the 117 studies reviewed, outcome measures were categorized into themes such as physical conditioning and exercise, physiological and anthropometric factors, training and prevention strategies, equipment and technology, assessment and prediction of G-tolerance, physiological effects of high-G exposure, external influences, and G-performance in female pilots.

G-Performance in Female Pilots

Early foundational research on G-tolerance established the physiological benchmarks for human performance under high Acceleration (5). Both studies consistently reported that women exhibit strong physiological tolerance and operational performance under high-G conditions, suggesting a trend toward gender parity in high-performance aviation settings (15, 16). Notably, muscular strength was maintained post-exposure in Chelette et al.'s study (16), and participants in Zhang's study were able to complete 3-minute simulated sorties without performance decline (15). Interestingly, Chelette et al. observed that women experienced less cerebral desaturation than men, hinting at a potential female-specific physiological advantage during high-G exposure (16). Additionally, no adverse cardiac effects or negative impacts on the menstrual cycle were reported, reinforcing the view that high-G environments do not compromise female physiological stability (16) [Supplementary Appendix S4].

Despite shared conclusions regarding female tolerance to high-G, the studies diverged in their findings on oxygen saturation and equipment performance. Zhang (15) found that the ATAGS anti-G suit was associated with significantly lower arterial and cerebral oxygen saturation levels, even though subjective G-tolerance was reported as higher. In contrast, Chelette et al. (16) reported no such physiological drawbacks across different training scenarios. This inconsistency may be due to equipment-specific factors—Zhang noted that the ATAGS suits were prototype models not custom-fitted to female subjects, potentially affecting both comfort and performance outcomes (15). Chelette et al. focused on long-term adaptation to G-exposure rather than equipment-specific trials, which could explain the lack of such discrepancies (16).

There are marked differences in methodology. Chelette et al. (16) employed a longitudinal, conference-report-based design focusing on multiple months of G-exposure, providing broader insight into long-term adaptation. In contrast, Zhang (15) conducted a cross-sectional observational study using brief, 3-minute centrifuge simulations to measure acute responses with high-resolution physiological data. Zhang's use of continuous monitoring tools (e.g., EMG, %rSO2, %SaO2) allowed for a fine-grained physiological assessment, whereas Chelette et al. offered more generalized performance trends over time. The methodological contrast reflects different research goals—operational readiness vs. technical suit evaluation. The populations differed in scale and focus. Chelette et al. (16) included both men and women (exact numbers unspecified), enabling gender comparisons and the exploration of menstrual cycle effects. Zhang (15), on the other hand, studied six female participants, aiming to represent typical users of COMBAT EDGE and ATAGS systems. Chelette et al. uniquely assessed whether menstrual cycle phase impacted performance, finding no significant effect on task completion or physiological adaptation (16). Zhang's study did not account for hormonal variables, focusing instead on equipment differences, which may limit the generalizability of its findings across different physiological states (15). Rausch et al. (26), the only randomized controlled trial in this review, included both male and female participants and evaluated the impact of training interventions, providing evidence for effective AGSM performance improvements in women. Smith (54), using observational methods, analyzed physical and cardiovascular predictors of G-tolerance in a mixed-gender fighter pilot sample. While not exclusively focused on women, Smith's study contributes important gender-comparative data, especially in terms of anthropometric and strength-related variables.

Despite growing interest in women's performance under G-stress, there remains a significant lack of large-scale, longitudinal studies with detailed physiological and operational metrics. Only Chelette et al. addressed menstrual cycle considerations, and no studies explored psychological stress, decision-making under pressure, or in-flight performance in real-world missions (15, 16). Additionally, neither study systematically investigated how equipment design could be optimized for female physiology—a gap particularly evident in Zhang's findings about suit discomfort (15). Comparing these findings underscores the need for standardized measurement protocols in future research on female high-G performance. The data strongly support the inclusion of women in high-performance aviation roles. However, future research should address ergonomic and physiological equipment compatibility, explore longer-duration cognitive and psychological effects, and ensure inclusive design standards for training and protection systems. These findings also advocate for custom-fitted protective gear for women, as ill-fitting equipment can compromise both safety and performance, even when physiological tolerance is high (15, 54).

Anthropometric Factors Related to G-Force Tolerance

A consistent pattern across multiple studies was the influence of physiological and anthropometric factors on G-tolerance. Height, blood pressure, body mass index (BMI), and autonomic cardiovascular responses were repeatedly shown to impact G-LOC risk and tolerance thresholds (5, 9, 56, 91, 92, 114, 129). Specifically, BMI and early heart rate (HR) response during G exposure emerged as strong predictors of performance in centrifuge tests, suggesting the critical role of rapid baroreflex activation (9). Similarly, studies by Sundblad et al. and Eiken et al. highlighted the importance of vascular responses and vasoconstrictor reserve as key mechanisms supporting G-tolerance (90, 92). Another recurring theme was the protective effect of the Anti-G Straining Maneuver (AGSM) and centrifuge-based training, both of which were reported to improve G performance, although they were undervalued or inconsistently practiced in certain cohorts, such as the Chinese aircrew (101) [Supplementary Appendix S5].

Despite some shared conclusions, notable discrepancies exist. For example, Harel et al. (129) found that taller pilots with lower systolic blood pressure were more prone to G-LOC, while Park et al. (72) argued that anthropometric and physiological characteristics were unreliable predictors of G-duration tolerance. This suggests that other unmeasured factors—possibly neurological, psychological, or genetic—may contribute significantly to G-tolerance variability. Furthermore, although Shin and Jee (2019) (140) did not find significant differences in G performance based on ACTN-3 genotype, earlier work by Shin (2018) (71) hinted at a possible advantage in 'RR' genotype carriers. These inconsistencies highlight the need for larger genetic and multifactorial studies.

Most studies employed observational designs, with cross-sectional and cohort approaches being dominant. Experimental settings varied: some utilized real operational flight data (e.g., Harel et al. (129)), while others conducted centrifuge simulations (e.g., Tu et al. (9), Gillingham (5)) or laboratory-based autonomic tests (e.g., tilt tests, cold pressor tests) (90, 92, 141). Studies with more rigorous physiological monitoring (e.g., beat-to-beat blood pressure, heart rate variability) provided deeper mechanistic insights, whereas questionnaire-based studies like Cao et al. (101) offered behavioral and experiential data but lacked objective physiological verification. The populations examined ranged from student pilots and cadets to experienced fighter pilots, with most participants being young adult males (9, 14, 56, 70-72, 90-92, 101, 114, 141-143). Few studies included women (e.g., Gillingham (5)), which limits generalizability. Cultural and institutional contexts also played a role; for instance, centrifuge training was less valued among Chinese aircrew (101), contrasting with its formal integration into Western air force protocols (5). Furthermore, regional differences in physical training emphasis (aerobic vs. anaerobic) could explain variability in outcomes, as aerobic fitness alone was not consistently protective (101).

Although widely studied, few papers integrated genetic, neurological, physiological, and behavioral variables into a single model. Genetic aspects, such as ACTN-3 polymorphism, were underexplored, and when addressed, sample sizes were small and results inconclusive (14, 71, 140). There is also a lack of longitudinal research, which could assess changes in G-tolerance over time, across aircraft types, or in aging pilots. Moreover, psychological resilience and cognitive performance under G-load remain largely unaddressed despite their operational relevance. Collectively, these findings suggest that pilot selection and training programs should adopt a multifactorial, personalized approach, incorporating cardiovascular reflex testing, body composition analysis, and tailored physical training regimens. Standardizing protocols for G-tolerance assessment, such as implementing mandatory early centrifuge exposure and improved AGSM training, could reduce the incidence of G-LOC. Future research should also investigate genetic and autonomic markers as predictors of individual G-performance capacity, and extend inclusion to diverse and aging populations to improve ecological validity.

Physiological Effects of High-G Exposure

Several studies consistently reported that exposure to +Gz forces induces both acute and chronic physiological responses, with recurring emphasis on cerebral oxygenation, cardiovascular adjustments, and protective strategies such as the Anti-G Straining Maneuver (AGSM) and anti-G suits (6, 55, 69, 89, 112, 115, 121, 136-138). These findings suggest a clear trend toward the integration of countermeasures and conditioning strategies to improve G tolerance and mitigate the risk of G-LOC. Many studies (6, 55, 69, 105, 115, 121) observed that repeated G exposure leads to adaptation, improving cerebral perfusion, vascular responses, and autonomic control. Other studies demonstrated that dehydration, low aerobic fitness, or inadequate technique can limit these benefits (89, 112, 115) [Supplementary Appendix S6].

Using instrumented training tools, such as centrifuge protocols, electrical impedance tomography (EIT) (105), echocardiography (123, 128), and SPECT imaging (99), revealed common patterns of reduced cerebral blood flow, increased hemoconcentration, and ocular or cognitive disturbances, all of which may impair flight performance. In contrast to Covertino (6), who found clear physiological adaptation through repeated G exposure, Eiken et al. (89) and Kurihara et al. (112) showed that cerebral oxygenation may remain depressed during sustained acceleration, indicating a potential ceiling for adaptation. This inconsistency might be explained by differences in exposure duration and anti-G suit functionality. While Siitonen et al. (99) suggested positive pressure breathing (PBG) as a less fatiguing alternative to AGSM, Yang et al. (105) highlighted the variability in AGSM performance, where teachers showed better pulmonary efficiency than students. Noddeland et al. (136) found significant renal strain without anti-G suits, contrasting with the absence of adverse effects in pilots equipped with G-protection.

Furthermore, while Assa et al. (128) and Ozturk et al. (123) found no significant structural cardiac changes with prolonged G exposure, Oliveira-Silva & Boullosa (115) observed acute vagal withdrawal and HRV suppression, suggesting transient autonomic shifts without long-term structural consequences. Although all studies used observational designs, methodologies varied from controlled centrifuge experiments (69, 121, 123) to in-flight or simulated flight scenarios (55, 99, 105, 115). Imaging and physiological measurement techniques ranged from SPECT (99), NIRS (112), and echocardiography (123, 128), to real-time lung imaging via EIT (105).

While some studies (105, 138) used in vitro models or modeling tools to simulate brain and lung stress, others prioritized in vivo measures, including blood biomarkers (69), HRV (115), and visual function tests (105, 121). These methodological differences shaped both the sensitivity of detection and the scope of conclusions. Studies involving quantitative tools like impedance tomography (105) and spectroscopic brain monitoring (112) provided deeper mechanistic insights than those based solely on pre/post comparisons (121, 123, 136).

Populations varied from experienced military pilots (6, 69, 115, 123, 128) to novices or students in medical and aerospace training (105, 137). Geographic diversity included studies from North America (6, 55, 138), Europe (89, 99, 136), Asia (69, 105, 112, 121, 137), and South America (115), revealing some regional differences in protocols and aircraft capabilities. Performance and adaptation also differed based on experience level: Yang et al. (105) and Ercan & Gunduz (13) found that more experienced or older pilots had superior AGSM execution and cognitive resilience, while younger or novice participants demonstrated greater physiological fluctuation. Most participants were healthy young men, highlighting an ongoing gender and age gap in this research area. None of the studies included female pilots in their analysis. Despite extensive physiological assessments, few studies addressed long-term cognitive outcomes or neuropsychological adaptation. Only Ercan & Gunduz (13) explicitly examined cognitive functions, while Gillingham (55) and Guillaume et al. (138) alluded to the mechanical and perceptual challenges posed by high-G maneuvering.

There is a clear lack of longitudinal data assessing AGSM retention or adaptation post-training (most studies assessed acute effects only), and minimal research exploring interactive effects between hydration, thermoregulation, and G-force performance. Furthermore, visual system vulnerabilities remain underreported, with Tsai et al. (121) being one of the few to explore contrast sensitivity and ocular anatomy under G-loads. Comparing these findings underscores the need for standardized assessment tools across training environments to evaluate G-tolerance, cerebral perfusion, and AGSM quality. The diversity in study settings and methods reveals promising insights but limits meta-analytic interpretation. There is strong evidence that AGSM, anti-G suits, and PBG remain essential in preventing G-LOC, but individual physiological variability requires more personalized countermeasure protocols. Future studies should prioritize long-term monitoring, female inclusion, and integration of neurocognitive and biomechanical domains to reflect real-flight complexity. Innovative technologies like EIT, wearable sensors, and AR/VR simulations could revolutionize AGSM training, offering both objective feedback and immersive learning environments.

Training and Prevention to Increase G-Tolerance

Several studies consistently reported that AGSM training effectively improves +Gz tolerance, both in novice and experienced pilots, suggesting a strong trend toward embedding structured AGSM protocols in fighter pilot training (24, 26, 53, 104, 126). Common across these studies was the finding that timely, well-executed AGSM, often supported by muscle conditioning and biofeedback mechanisms, led to significant gains in physiological resistance to high-G environments. Across the studies, centrifuge-based training emerged as the gold standard for exposure and testing (26, 52, 53, 104, 111, 126), often accompanied by feedback tools such as surface electromyography (EMG) (26, 126) or head-up display (HUD) video review (24, 52). In addition, AGSM errors, such as rapid breathing, shallow inhalation, and vocalization under G-loads, were frequently reported (24, 52), highlighting the need for continuous reinforcement and skill retention programs [Supplementary Appendix S7].

There was also a trend toward integrating functional strength training into pilot conditioning, as shown in Rausch et al. (26), who reported significant increases in neck and core muscle strength and improved efficiency during G-loads. This aligns with Slungaard et al. (82), who validated the structure and relevance of a targeted physical conditioning program for RAF aircrew. While Lyons et al. (24) and Geng et al. (104) reported successful correction of AGSM deficiencies and significant improvements in G-tolerance post-training, Sah et al. (126) noted variability in muscular recruitment, with some participants showing limited correlation between trunk muscle activation and improved G-tolerance, suggesting individual variability in response to AGSM training.

Moreover, Plioutsias & Karanikas (137) raised concerns that feedback overload in multi-tasking simulations may hinder pilot performance, particularly when feedback is delivered via a single sensory modality (e.g., visual cues only). This contrasts with the findings of Cammarota & Whinnery (52), where video-based feedback was successfully integrated into centrifuge training without evidence of sensory saturation, possibly due to the simpler, controlled environment. In terms of training structure, Smith (144) found that the RAAF's adaptive and smaller-scale approach led to faster individual adjustments, whereas the USAF's standardized protocols emphasized consistency across squadrons. These differences reflect broader cultural and organizational variations influencing training outcomes. The included studies primarily employed observational designs (24, 52, 53, 104, 111, 126, 144), with one randomized controlled trial (26) and one small-sample exploratory study involving two participants (104). Although single-subject case studies were excluded per our criteria, this particular study was included due to its structured design, use of instrumented physiological measurements, and comparative analysis across multiple subjects, which allowed for limited cross-subject interpretation. No single-subject case studies were analyzed.

While most observational studies focused on descriptive improvements in G-tolerance or AGSM performance, the RCT by Rausch et al. (26) allowed for causal inference between functional training and physiological outcomes. Studies like Sah et al. (126) and Cammarota & Whinnery (52) used quantitative EMG measures to evaluate muscle activity during AGSM, while others relied more heavily on performance observation and pilot self-reporting (24, 54). The inclusion of feedback tools, such as HUD recordings (24) and real-time monitoring (52), added depth to performance evaluation and revealed highly correctable AGSM errors. The studies focused on diverse pilot populations from the USAF (24, 26, 52-54), RAF (82), RAAF (144), Indian Air Force (126), Japanese Air Self Defense Force (111), and a South European Air Force (137). These geographic and institutional differences influenced both the resources available and the training philosophies applied.

For instance, Geng et al. (104) described pilots with low baseline G-tolerance, who benefited from targeted centrifuge-based AGSM and PBG (pressure breathing) training, while Sah et al. (126) evaluated ab-initio pilots in a controlled training environment. The inclusion of both novice and experienced pilots across studies offers insight into training scalability and adaptability. Female participation was minimal, with only Rausch et al. (26) and Smith (144) reporting mixed-gender samples—highlighting a gap in gender-representative data. Despite multiple studies assessing the physiological benefits of AGSM and related training, few addressed the cognitive or neuropsychological aspects of G-force exposure, such as reaction time, mental workload, or decision-making capacity. Furthermore, long-term retention of AGSM skills remains underexplored—most studies measured outcomes immediately post-training without follow-up assessments (24, 26, 53, 126). Also lacking were investigations into the integration of advanced technologies, such as virtual or augmented reality environments for AGSM practice, which may offer scalable and immersive training alternatives. The combined effect of environmental factors, such as helmet weight or NVG use, was touched on by Rausch et al. (26) but warrants deeper study.

Comparing these studies reveals that while AGSM training is highly effective, its success depends on consistent reinforcement, real-time feedback, and physical preparedness. Findings highlight the benefit of integrating functional strength programs, as well as the importance of feedback-rich environments to detect and correct technique flaws early. There is a clear need for standardized assessment protocols, gender-diverse samples, and longitudinal studies to track skill retention. Furthermore, exploring multisensory feedback integration and cognitive resilience under G will better align future research with the realities of modern combat aviation.

Physical Conditioning and Exercise for Pilots

Several studies consistently demonstrate that improved muscular and aerobic fitness correlates with enhanced G-tolerance, reduced physiological strain, and lower musculoskeletal injury risk among fighter pilots and cadets (12, 94, 98, 102, 117). Aerobic capacity (VO_2 max) frequently emerges as a key factor, emphasizing its importance in pilot performance (49, 81, 97). Additionally, musculoskeletal strain and spinal issues, particularly among high-G pilots, are commonly reported, highlighting the occupational toll of repeated G-force exposure and the need for strength-based interventions (68, 88, 145). Mental fatigue has also gained attention as an impactful, non-physical factor affecting pilot readiness (66, 116). In contrast to studies suggesting that aerobic training improves G-tolerance (98, 135), others, such as Kölegård et al. (87), found no significant difference in G-tolerance between endurance-trained, strength-trained, and untrained individuals, suggesting that relaxed G-tolerance might be independent of general fitness. Furthermore, while Balldin et al. (88) found no improvement in G-tolerance following abdominal training, other studies, like Tesch et al. (12) and Epperson et al. (48), showed significant improvements from strength training, likely due to differences in training specificity and targeted muscle groups [Supplementary Appendix S8].

Most studies employed observational cohort or cross-sectional designs, which offer valuable real-world insights but are limited in establishing causal relationships (81, 94, 135). A few studies utilized randomized controlled trials (RCTs), such as Sovelius et al. (94), Balldin et al. (88), and Tesch et al. (12), providing stronger evidence on intervention effectiveness. Additionally, quasi-experimental studies, such as those by Balldin et al. (86), allowed controlled pre-post comparisons without full randomization, which is often more feasible in military settings. The majority of studies focused on male fighter pilots from various countries, including Australia (81), Finland (68, 94, 145), Poland (97), Brazil (116), South Korea (12), and China (66), indicating some diversity. However, female pilots and non-Western cohorts remain underrepresented. Contextual differences—such as aircraft type, G-force levels, and training infrastructure—likely influenced outcomes. For instance, Finnish Air Force studies emphasized spinal health and long-term musculoskeletal impact (68, 145), while Chinese and Korean studies focused more on training interventions and aerobic outcomes (66).

Despite the extensive research on aerobic and strength training, few studies have addressed the long-term mental health impacts of repeated G-exposure, gender differences in physiological responses and G-tolerance, or integrated programs that combine physical, cognitive, and nutritional interventions. Additionally, there is a lack of longitudinal studies that track pilots over several years to assess the sustained effects of conditioning programs on career longevity or injury rates. These findings emphasize the need for standardized physical assessment protocols, especially for muscular fitness and G-tolerance. The results also support a balanced training approach combining aerobic endurance, strength training, and recovery strategies to enhance operational performance. For policy and practice, implementing tailored fitness programs based on pilot type (e.g., high-G vs.

low-G) and incorporating tools to monitor mental fatigue (e.g., the FFS scale) could optimize pilot readiness. Future research should prioritize diverse populations, randomized trials, and international studies to help establish global best practices in military aviation health.

Equipment and Technology for Enhancing G-Tolerance

Several studies consistently reported that anti-G protection systems—such as pressure breathing during G (PBG), abdominal restraints, and lumbar supports—enhance pilot comfort, tolerance, or physiological stability without compromising performance. Notably, Oksa et al. (95), Eiken et al. (84), and Wood et al. (79) all found improved or maintained G-tolerance when novel or supplementary protective systems were introduced. Most studies used centrifuge testing or simulated aerial combat maneuvers, typically involving trained pilots or test subjects. Recurring themes include perceived exertion, oxygen saturation, visual symptoms, G-LOC, and muscle engagement during anti-G straining maneuvers. In contrast to the study by Oksa et al. (95), which found increased effectiveness in AGSM with lumbar support, Eiken et al. (84) observed no significant difference in overall comfort or performance with the addition of an internal abdominal bladder restraint. Moreover, Wood et al. (79) reported that PBG improved G-endurance slightly but did not significantly alter physiological metrics such as oxygen saturation or perceived exertion. Acceptance of the PBG system also varied by aircraft type, with Travis and Morgan (47) noting greater acceptance among F-16 pilots compared to F-15 pilots—an inconsistency potentially tied to cockpit ergonomics or aircraft performance [Supplementary Appendix S9].

While most studies were randomized controlled trials (RCTs) or controlled experimental studies, one study (47) employed a cross-sectional observational design, focusing on pilot-reported outcomes rather than physiological measurements. This difference in methodology may explain why their findings leaned more toward subjective health effects than physiological performance. Studies using RCTs or controlled exposures (84, 95, 146) tended to offer more precise, quantifiable data on outcomes such as EMG activity, heart rate, or G-LOC. In contrast, observational methods provided broader insights into pilot experience and system acceptance. Most studies involved trained military pilots or centrifuge test subjects, although the level of training and operational context varied. One study (146) included untrained pilots, which may explain the differing G-tolerance outcomes under supination. Another study (47) used a large sample of operational pilots, while others (85, 110) focused on small, highly specialized participant groups. Few studies explicitly described geographic or cultural context, though one (110) involved Swedish pilots and U.S.-based centrifuge facilities. This lack of contextual detail limits generalizability and suggests that context-specific design and ergonomics may play a greater role than previously reported.

Despite multiple studies evaluating physiological performance under high G-forces, few addressed long-term musculoskeletal effects, system integration in cockpit environments, or gender-based differences. Furthermore, while various technologies were compared (e.g., hydrostatic vs. pneumatic suits) (84), the actual mechanism behind improved G-tolerance remains under-explored. Only one study (109) addressed heat stress, a crucial factor in operational settings, indicating a gap in environmental interaction research. Comparing these findings underscores the need for standardized measurement protocols and broader participant diversity in future anti-G research. While innovations like PBG, lumbar supports, and supination offer promise, inconsistencies in effectiveness highlight the importance of context, individual physiology, and integration with aircraft systems. Future studies should explore gender differences, long-term fatigue or injury risks, and incorporate larger, more representative samples to improve applicability and design refinement.

Risks and Impacts of High-G Environments on Pilots

Several studies consistently reported a high prevalence of G-induced visual and cognitive disturbances, including greyout, blackout, A-LOC, and G-LOC symptoms across air forces globally (43, 75, 76, 78, 118, 122, 134). This trend suggests a universal physiological response to +Gz exposure, regardless of nationality or aircraft type. Furthermore, studies highlighted the positive impact of centrifuge training and targeted physical training, particularly resistance training and cervical spine programs, in improving G-tolerance and reducing injury risk (42, 46, 65, 76, 108). In contrast to Galvagno et al. (46), who reported preliminary findings with no control group, Chayrez et al. (42) provided more robust data indicating statistically significant improvements in cervical endurance following an 8-week spine training program. Similarly, while Rickards & Newman (78) and Yilmaz et al. (122) documented high rates of A-LOC and G-LOC, Slungaard et al. (76) reported a decrease in G-LOC prevalence, potentially due to enhanced training interventions. The inconsistency in G-LOC incidence may be explained by variations in aircraft, pilot experience, or implementation of countermeasures [Supplementary Appendix S10].

While most studies were observational and retrospective in design (17, 43, 45, 46, 76-78, 83, 108, 118, 122), Hormeño-Holgado & Clemente-Suárez (134) conducted a non-randomized experimental study, allowing for direct measurement of physiological and psychological responses during combat maneuvers. This contrasts with survey-based studies that relied on self-reporting, which can introduce recall bias. Additionally, newer studies like Keskimölö et al. (17) employed MRI imaging to objectively assess degenerative changes, representing a methodological advancement in anatomical outcome tracking. Populations varied widely—from student pilots in the U.S. and Finland (42, 46, 65), to operational aircrew in Australia, Turkey, China, Brazil, and the UK (43, 76-78, 83, 108, 122, 134). Notably, younger, less experienced pilots were often identified as being at higher risk for G-LOC (134), while cadets and students were the focus of training interventions (42, 65). Differences in aircraft types, G-onset rates, and geographic training protocols may have influenced the variability in outcomes, with F-16 pilots generally facing the highest G-LOC risk due to rapid onset forces (122, 134). Despite numerous studies on G-LOC and visual disturbances, few addressed gender-specific responses, an important omission given the growing number of female fighter pilots entering high-performance aviation roles (65).

There is also limited research on the longitudinal effects of cumulative G-force exposure beyond the 5-year scope of Keskimölö et al. (17). Moreover, the role of psychological resilience, cognitive training, or neurocognitive adaptation to high-G stress remains largely unexplored. The lack of randomized controlled trials (RCTs) limits the ability to draw causal conclusions about the efficacy of training interventions. Comparing these findings underscores the need for standardized outcome measures, especially for G-LOC events and training efficacy. The recurrent emphasis on neck/spine strength and resistance training indicates a potential area for policy standardization across air forces. Future research should incorporate RCTs, gender-specific analysis, and multi-national data pooling to refine prevention strategies and tailor G-tolerance training programs effectively.

Assessment and Prediction of G-Tolerance

Several studies consistently reported that effective Anti-G Straining Maneuvers (AGSM) and cardiovascular adaptations are crucial for enhancing G-tolerance and preventing G-LOC. For example, both Tu et al. (120) and Kim et al. (63) found that AGSM performance and heart rate responsiveness directly influence high-G profile tolerance, highlighting a physiological synergy between active muscle straining and cardiovascular regulation during high-G stress. Another common trend was the use of EMG monitoring (particularly of the gastrocnemius muscle) to detect impending G-LOC, as seen in the studies by Choi et al. (64) and Kim et al. (63). These studies provided a foundation for developing real-time G-LOC warning systems, enhancing pilot safety during high-G maneuvers. In terms of technology, near-infrared spectroscopy (NIRS) was also frequently used to monitor cerebral oxygenation as a predictor of consciousness loss, as demonstrated in studies by Ryoo et al. (20) and Onozawa et al. (106). In contrast to studies that emphasized physiological indicators like HR variability and EMG signals, Park et al. (58) concluded that physical fitness or condition had no significant impact on G-LOC in experienced aviators. This divergence suggests that once a certain level of conditioning is achieved, skillful execution of AGSM becomes a more decisive factor. Moreover, Whinnery & Forster (41) proposed a universal G-LOC curve independent of onset rate. Ryoo et al. (20) emphasized that repeated +Gz pulses led to faster and deeper drops in regional cerebral oxygen saturation (rSO_2), implying variability in outcomes based on acceleration profile [Supplementary Appendix S11].

Most studies employed cross-sectional observational designs, often using human centrifuge data to assess tolerance and physiological markers (24, 52-54, 104, 111, 126) . However, Stevenson & Scott (73) and Onozawa et al. (106) used randomized controlled trials, providing higher levels of evidence on intervention effects such as AGSM muscle tensing and medication (loratadine). Dissertation studies like those by Sharma and Kumar provided in-depth but often institution-specific insights, useful for practical military application yet sometimes limited in generalizability (124, 125).

Most studies focused on young male military aviators, leaving female and older populations largely underrepresented, despite some mention in Ryoo et al. (20) and Kuo et al. (119). The Korean Air Force featured prominently in studies involving EMG and AGSM effectiveness (63, 64), whereas USAF and NATO studies often focused on long-term centrifuge datasets and medical evaluation standards (40, 41). Genetic studies such as those by Shin et al. (60) and Chiang et al. (147) introduced new dimensions by examining ACE and ACTN3 genotypes in relation to G-tolerance, a line of inquiry missing in earlier works. Despite the breadth of research on physiological predictors, there is a significant lack of longitudinal studies tracking G-tolerance adaptation over a pilot's career span. Additionally, female pilots remain grossly underrepresented, limiting the applicability of findings to mixed-gender aircrew. Very few studies examined psychological or cognitive factors such as reaction time or decision-making under high-G stress, despite their operational importance. Also, while EMG and NIRS are widely used for monitoring, there is little integration of these modalities into wearable, operational cockpit systems beyond research settings.

Comparing these findings underscores the need for standardized physiological metrics (like HRV, EMG decay trends, and cerebral rSO_2 thresholds) across studies to reliably predict and train for G-tolerance. For future research, integrating wearable sensors, exploring gene-environment interactions, and including diverse populations will be critical for developing personalized training and protection systems in high-performance aviation. Furthermore, adopting a multimodal prediction model combining EMG, NIRS, cardiovascular responses, and possibly genomic data could greatly enhance predictive accuracy for G-LOC and allow for real-time in-flight countermeasures.

External Factors Affecting G-Tolerance

Several studies consistently reported that physiological stressors such as dehydration, fatigue, or sleep quality significantly impact G-tolerance and pilot safety, suggesting a trend toward recognizing human performance factors as critical to aviation readiness (36, 57, 127, 139). Across all studies, aeromedical fitness and operational performance were central themes. Whether assessing fluid loss (127), sleep quality (57), or aerobic capacity (36), each study highlighted a measurable physiological variable as a predictor of G-tolerance or flight safety. In contrast to Zeigler & Acevedo (36), who found aerobic capacity testing beneficial and not detrimental to G-tolerance, Khomenko et al. (139) noted that extended physical stress (long-duration flight simulation) impaired G-tolerance, suggesting a potential short-term negative impact of fatigue even in aerobically fit individuals. This may reflect a contrast between chronic fitness adaptations versus acute fatigue effects [Supplementary Appendix S12].

Another divergence appears in Levkovsky et al. (127) who emphasized hydration status, versus Jeong et al. (57) who found no significant difference in body composition or physical performance measures but did link sleep quality to G-tolerance—implying cognitive recovery factors may at times outweigh physical conditioning. While most studies were observational in design (57, 127, 139), only Zeigler & Acevedo (36) used a systematic review, offering a broader synthesis of findings rather than original data collection. Khomenko et al. (139) applied a pre-post experimental approach using a centrifuge to simulate flight stress, whereas Levkovsky et al. (127) used real in-flight measurements, adding ecological validity but limiting control over confounders.

Measurement tools also varied: hydration was gauged via bodyweight and urine specific gravity (127), G-tolerance via centrifuge performance (57, 139), and aerobic capacity via VO_2 max estimation in the literature (36). This heterogeneity limits direct comparisons but enriches the multidimensional view of aviator readiness. Populations ranged from Israeli Air Force aviators (127) to Republic of Korea cadets (57), with others focusing broadly on U.S. Air Force pilots (36) or Russian military personnel (139). This geographic and occupational diversity may influence physiological baselines, operational norms, and environmental exposures. Notably, Jeong et al. (57) included a larger sample (n=157) compared to Khomenko et al. (139), who studied only six individuals. The broader sample enhances statistical power, while the small-sample centrifuge study allows for precise physiological monitoring under controlled stress. Despite multiple studies on hydration, fitness, and fatigue, few addressed cognitive or psychological resilience (16, 24, 26). Additionally, gender-specific analysis is missing, as most studies used either all-male or undefined gender samples. There is also limited longitudinal data—most outcomes reflect immediate effects of stress or performance but not long-term adaptation or health outcomes.

Comparing these findings underscores the need for standardized physiological monitoring protocols in aviator training, particularly regarding sleep quality, hydration, and aerobic fitness. Future research should aim for integrative models that include both acute and chronic factors, and expand to more diverse populations, including women and older pilots. These comparisons also inform policy: integrating routine VO_2 max assessments (36), hydration checks pre-/post-flight (127), and sleep quality screening (57) could improve pilot safety and performance in high-G environments.

Gaps in Literature and Future Recommendations

Despite the broad and growing body of research on G-tolerance and high-G exposure, several critical gaps persist in the literature that hinder the development of inclusive, effective, and predictive models of pilot performance under gravitational stress.

Physiological and Anthropometric Factors

There is a marked lack of longitudinal and career-spanning studies on physiological and anthropometric variables. Most current research relies on cross-sectional or short-term pre-post designs, which offer limited insight into how G-tolerance evolves or deteriorates over the course of a pilot's career. Longitudinal studies are essential to understand the cumulative effects of G-force exposure on musculoskeletal health, neurocognitive resilience, and cardiac remodeling, and to establish evidence-based practices for long-term health monitoring in aviation professionals (17, 128, 141).

Cognitive and Psychological Resilience

There is insufficient integration of cognitive, psychological, and operational factors in existing research. While physiological indicators such as heart rate variability, EMG activity, and oxygen saturation are frequently studied, cognitive load, psychological resilience, and decision-making under G-stress are often neglected. Emerging findings on mental fatigue (116) and sleep quality (57) suggest that cognitive readiness is a critical yet under-researched determinant of performance and a key factor in mitigating the risk of G-LOC.

Training and Operational Strategies

Although AGSM training and centrifuge testing are established practices, the literature reflects inconsistency in their application and evaluation. The effectiveness of physical conditioning, skill retention, and integrated training protocols is rarely studied in long-term contexts. There is also limited understanding of how different training modalities interact with physiological and cognitive factors to enhance overall G-tolerance.

Equipment and Real-Time Monitoring Technologies

There is a notable gap in the development and operational implementation of wearable, real-time monitoring systems. Although technologies such as EMG and near-infrared spectroscopy (NIRS) have proven effective in detecting pre-LOC physiological markers (20, 63), few studies have examined how these technologies can be integrated into cockpit environments in a functional and non-intrusive manner (16, 20, 126). Bridging the divide between laboratory validation and real-world application remains a critical area for technological advancement.

Underrepresented Populations

One of the most salient issues is the underrepresentation of female pilots and the lack of gender-specific analyses. Although women have demonstrated physiological resilience in high-G environments comparable to that of men, the majority of studies continue to focus predominantly on male populations. Female-specific data remain limited, and sample sizes are often too small to draw robust conclusions (14-16). The influence of sex-based physiological differences, such as vascular compliance, body composition, and equipment fit, requires further investigation to inform the design of gender-inclusive protective systems and training protocols (72, 95).

Methodological Standardization

Another impediment to progress is the inconsistency in methodologies and the lack of standardization across studies. There is considerable variability in measurement protocols, ranging from centrifuge profiles to Anti-G Straining Maneuver (AGSM) scoring systems and definitions of G-tolerance. The absence of standardized physiological, cognitive, and performance metrics hampers cross-study comparability and undermines the development of universal benchmarks for G-tolerance (73, 107).

Environmental and Ergonomic Stressors

Finally, there is minimal research focused on the ergonomics of protective equipment and the interaction of environmental stressors with G-protection systems. Long-term musculoskeletal impacts and gender-specific fit issues related to anti-G suits are rarely addressed (95). Moreover, the combined effects of operational stressors such as heat, fatigue, and dehydration remain poorly characterized in the context of high-G environments (110, 127). The refinement of protective gear must be grounded in robust ergonomic and physiological data that account for the diversity of pilot populations and operational conditions.

CONCLUSIONS

This scoping review provides a comprehensive synthesis of the existing literature on G-force tolerance in fighter pilots, encompassing 117 studies across diverse geographic and methodological contexts. The findings demonstrate that G-tolerance is a multifactorial construct influenced by a combination of physiological and anthropometric characteristics, physical conditioning, proficiency in anti-G straining maneuvers (AGSM), genetic predispositions, and external factors such as fatigue, hydration, and sleep quality. While significant progress has been made in understanding the physiological adaptations to high-G environments and developing effective countermeasures, several critical gaps persist. Notably, the underrepresentation of female pilots, the scarcity of longitudinal research tracking career-span adaptations, and the limited integration of cognitive and psychological metrics in G-tolerance assessments highlight areas in need of further exploration. Moreover, methodological inconsistencies across studies hinder the establishment of standardized evaluation protocols, and the application of wearable monitoring technologies in operational settings remains limited. To advance the field, future research should adopt inclusive, multidisciplinary approaches that incorporate standardized physiological, cognitive, and ergonomic assessments. Longitudinal designs, gender-specific analyses, and the operationalization of real-time monitoring systems are essential to enhance the safety, performance, and occupational health of fighter pilots exposed to high-acceleration environments.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest or competing interests relevant to the content of this manuscript.

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João Bruno, Hugo Sarmento, and Raynier Montoro-Bombú conceptualized the review and developed the inclusion criteria. The same authors completed the screening and data extraction processes. All authors contributed to the creation of tables and figures. All authors participated in drafting, reviewing, and approving the final version of the manuscript.

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