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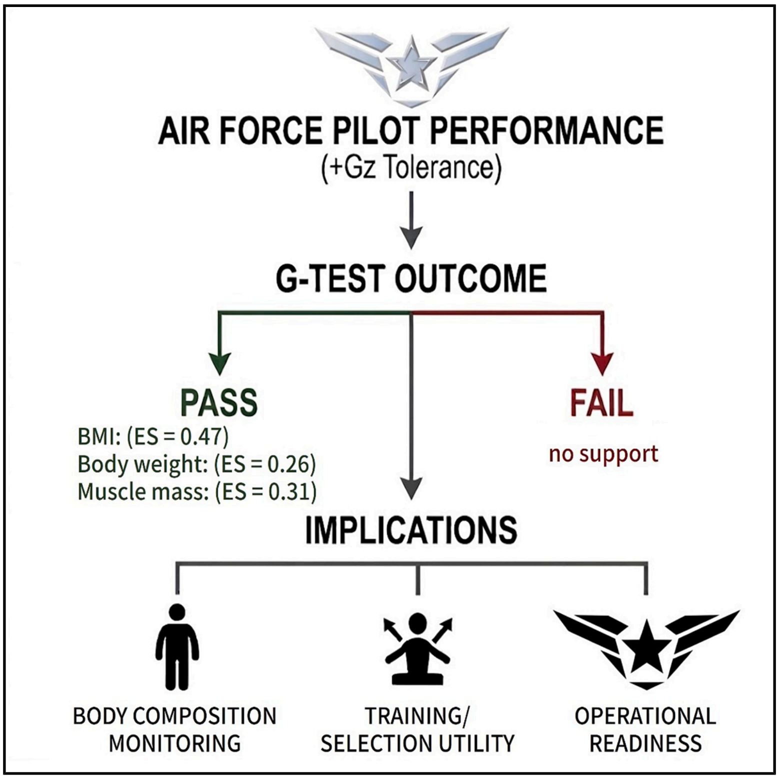
Does body composition influence air force pilots' resistance to high-G acceleration? A systematic review meta-analysis

Graphical abstract



Highlights

- BMI showed a moderate positive association with G-test pass outcomes
- Body weight and muscle mass showed small positive associations with +Gz tolerance
- Physical fitness variables did not differ significantly by G-test outcome
- Body composition may be a useful factor in pilot screening and training decisions

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In brief

Health sciences; Medicine; Occupational medicine; Military medicine

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Does body composition influence air force pilots' resistance to high-G acceleration? A systematic review meta-analysis

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SUMMARY

Understanding how body composition relates to tolerance of high +Gz is important for sustaining Air Force pilot performance, yet prior studies report mixed results. This study synthesized evidence on whether differences in body composition are associated with pass/fail outcomes on G-tests in pilots and cadets. PubMed and the Cochrane Library were searched for studies published since 2014, with Google Scholar used to supplement retrieval; ten eligible articles were meta-analyzed. Using R, the authors estimated effect sizes, tested heterogeneity, explored sub-variables, and assessed publication bias. The pooled results indicated moderate associations for body mass index (BMI) (effect size 0.47) and small associations for body weight (0.26) and muscle mass (0.31) with G-test outcomes, with low-to-moderate heterogeneity across analyses. In contrast, physical fitness variables did not differ between pass and fail groups. These findings support incorporating body composition assessment into training and selection decisions, and motivate mechanistic research linking composition, physiological strain, and operational readiness.

INTRODUCTION

The emergence of high-performance fighter jets and the Air Force's operation completely changed the game of modern war. The acceleration of high-performance fighter jets can reach +9 Gz or higher,[1] and the development of the latest models is also expected as the aerospace industry continues to develop. As such, fighter jets have made rapid progress with the intensive power of modern technology, and the physiological readiness of pilots to fly is also becoming important. As aircraft capabilities progress, maintaining adequate G-tolerance is increasingly critical for safe and effective flight operations.

Air Force pilots must have physical strength and abilities to overcome various physiological changes, including loss of consciousness due to gravity (G-LOC), hypoxia, cognitive dissonance, hearing loss, and flight illusion in the air environment.[2] Among them, G-LOC is considered a particular risk factor, and deaths from G-LOC have also been reported.[3] Furthermore, prior research has shown that approximately 8–20% of the military crew have experienced G-LOC,[4] which is caused by gravity (g-force) due to low inertial forces. Hematological variables cause a supergravity environment in which blood is concentrated toward the lower body due to the g-force.[5] This leads to a situation where there is no smooth supply of oxygen to the nervous system and brain that supports consciousness.[6] Therefore, identifying modifiable physiological and physical factors associated with G-tolerance is important for prevention strategies.

Since preventing G-LOC alone can prevent many casualties and property accidents, the physical strength and body composition of Air Force pilots are important factors maintained by Air Forces around the world. Therefore, it is necessary to clarify the relationship between body composition and G-resistance to improve the combat performance and conditioning of Air Force pilots; however, there are many conflicting results when looking at the results of previous studies. Also, studies of meta-analytic approaches that have comprehensively analyzed conflicting outcomes have not been documented. Existing reports vary in which body-composition and fitness indicators are emphasized, making it difficult to draw consolidated conclusions for screening and training.

Despite many studies demonstrating that military pilots suffer G-LOC with high Gz, there is a lack of clear indicators for the following questions: (1) which part of the pilot's body composition and fitness positively strengthens G-resistance?, and (2)

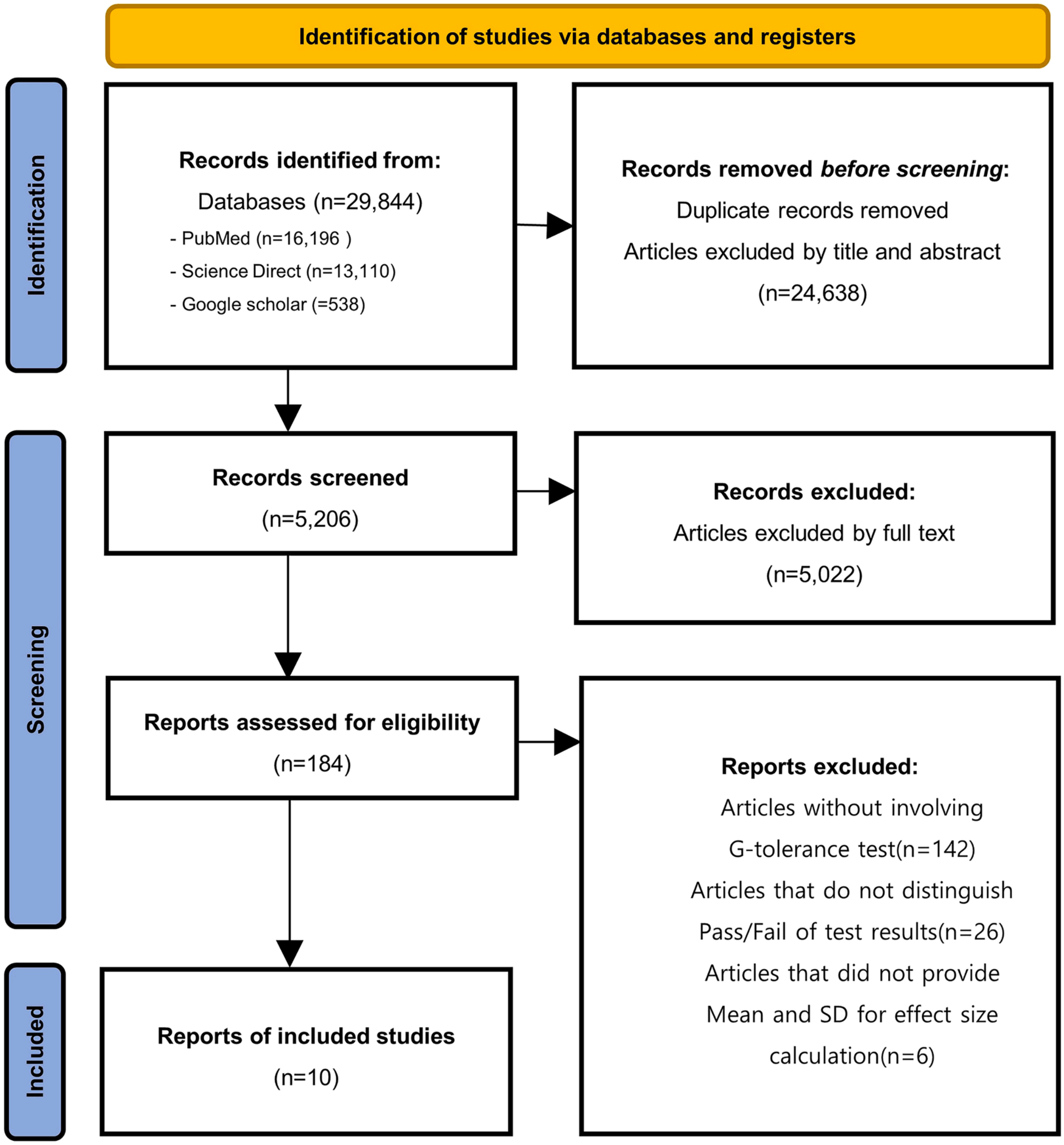

Figure 1. PRISMA flow diagram of study selection

Database searches identified 29,844 records; 184 full-text reports were assessed and 10 studies were included in the systematic review and meta-analysis.

what intervention methods (exercise prescriptions, and so forth) are effective for pilots as G-LOC prevention measures? Therefore, the purpose of this study is to answer these two research questions. Accordingly, this study conducted a systematic review and meta-analysis comparing G-test pass and fail groups to identify body-composition and physical-fitness factors most consistently associated with G-tolerance outcomes in military fighter pilots and pilot trainees. In addition, the meta-analysis study analyzes factors in body composition and fitness levels to offset the effects of high G-force values in military fighter pilots and is the first to combine answers to questions about whether training methods can be used.

RESULTS

As a result of the literature search, 29,844 studies were identified (Figure 1). A total of 184 studies were selected by removing duplicate papers and reviewing titles and abstracts. An additional 174 studies were excluded for the following reasons: the study did not conduct the G-test (n = 142), the study did not

Table 1. Characteristics of the selected articles

	Study and location	N (pass/fail)	Sex	Age (y)	G-tolerance test	Outcome
1	Shin & Jee, 2019 [11]; Korea	68 (31/37)	male	22.6 ± 0.75	+6 G_z/30 s	height, weight, BMI muscle mass, body fat 3 km-running, Push-up
2	Yun et al., 2019 [12]; Korea	138 (100/38)	male	23.3 ± 1.5	6 G_z/30 s	BMI
3	Shin & Son, 2022 [13]; Korea	20 (10/10)	male	25.6 ± 1.5	+8.5 G_z/15 s	height, weight BMI, muscle mass, body fat
4	Tu et al., 2020 [14]; Taiwan	530 (428/102)	male	p: 25.4 ± 1.0 f: 26.4 ± 1.7	9 G_z	height, weight
5	Park et al., 2016 [15]; Korea	55 (37/18)	male	p: 21.7 ± 0.9 f: 21.6 ± 0.7	+6 G_z/30 s	height, weight, BMI muscle mass, body fat
6	Jeong et al., 2023 [16]; Korea	72 (40/32)	male	23.8 ± 0.6	5 G_z/30 s	height, weight, BMI muscle mass, body fat
7	Sung et al., 2023 [17]; Korea	138 (79/59)	male	p: 23.7 ± 0.7 f: 23.4 ± 0.8	5 G_z/30 s	height, weight, BMI muscle mass, body fat 3 km-running, Push-up, Sit-up
8	Sung & Lee, 2024 [18]; Korea	115 (72/43)	male	20s	5 G_z/30 s	height, weight, BMI muscle mass, body fat 3 km-running, Push-up, Sit-up
9	Jeong et al., 2024 [19]; Korea	157 (87/70)	male	p: 23.2 ± 0.4 f: 23.1 ± 0.2	5 G_z/30 s	height, weight, BMI muscle mass, body fat, 3 km-running, Push-up, Sit-up
10	Tu et al., 2020 [20]; Taiwan	873 (829/44)	male	p: 23.5 ± 1.2 f: 23.6 ± 0.7	7.5 G_z/15 s	height, weight, BMI

f, fail; p, pass; BMI, body mass index.

divide the results into pass/fail groups ($n = 26$), and the study did not present mean and standard deviation data for calculating the effect size ($n = 6$). Finally, 10 studies[7–16] were included in the systematic review and meta-analysis.

Characteristics of participants

The comparative meta-analysis included a total of 2,166 participants from 10 individual studies according to performance in the gravitational acceleration test (pass, 1,713; fail, 453). All participants were male, aged in their twenties (mean ± standard deviation, 23.39 ± 1.62 years), with a height of 174.35 ± 1.16 cm, a weight of 70.83 ± 2.26 kg, a body mass index (BMI) of 23.12 ± 0.84 kg/m^2, a body fat of 16.21 ± 2.03%, and a muscle mass of 33.68 ± 0.92%.

Table 2. Quality assessment of the included studies by the Newcastle-Ottawa Scale

Author, Year	Selection	Comparability	Outcome	Total Score
Shin & Jee, 2019 [11]	★★★★	★★	★★	8
Yun et al., 2019 [12]	★★★★	★★	★	7
Shin & Son, 2022 [13]	★★★	★	★	5
Tu et al., 2020 [14]	★★★★★	★★	★★★	10
Park et al., 2016 [15]	★★★★★	★	★	7
Jeong et al., 2023 [16]	★★★★★	★	★	7
Sung et al., 2023 [17]	★★★★★	★	★	7
Sung & Lee, 2024 [18]	★★★★★	★	★	7
Jeong et al., 2024 [19]	★★★★★	★★	★	8
Tu et al., 2020 [20]	★★★★★	★★	★★★	10

The included studies were conducted in Korea[7–9,11–15] and Taiwan[10,16] and included either pilots[10] or prospective or pilot trainees.[7–9,11–15]

All studies reported a G-test using gravitational acceleration gondolas, and the Gz force received in the G-test was measured at +5 Gz in four studies[12–15] +6 Gz in three studies,[7,8,15] and +7.5 Gz,[16] +8.5 Gz,[9] and +9 Gz in one study each.[10] In addition, the G-test execution time was identified as 15 s,[9,16] or 30 s,[7,8,11–15] with no reported execution time in one study.[10]

Eight studies reported all body composition results,[7,9,11–16] while one study reported BMI[8] and one study[10] reported height and weight. Four studies reported physical fitness results,[7,13–15] three studies measured km-running, push-up, and sit-up tests,[13–15] and one study conducted only the 3 km-running and push-up tests.[9] All studies were cross-sectional studies, and body composition and physical fitness were presented as means and SD. The characteristics of the included studies are shown in Table 1.

Quality assessment

The qualitative evaluation of the included studies is reported in Table 2. The NOS scores of the included studies ranged from 5 to 10. Two studies were very good with 10 points, seven were good with 7–8 points, one was good with 5 points, and no studies were evaluated as poor.

Body composition meta-analysis

Data from participants were used to compare the body composition values of the pass ($n = 1,713$) and fail ($n = 453$) groups, for

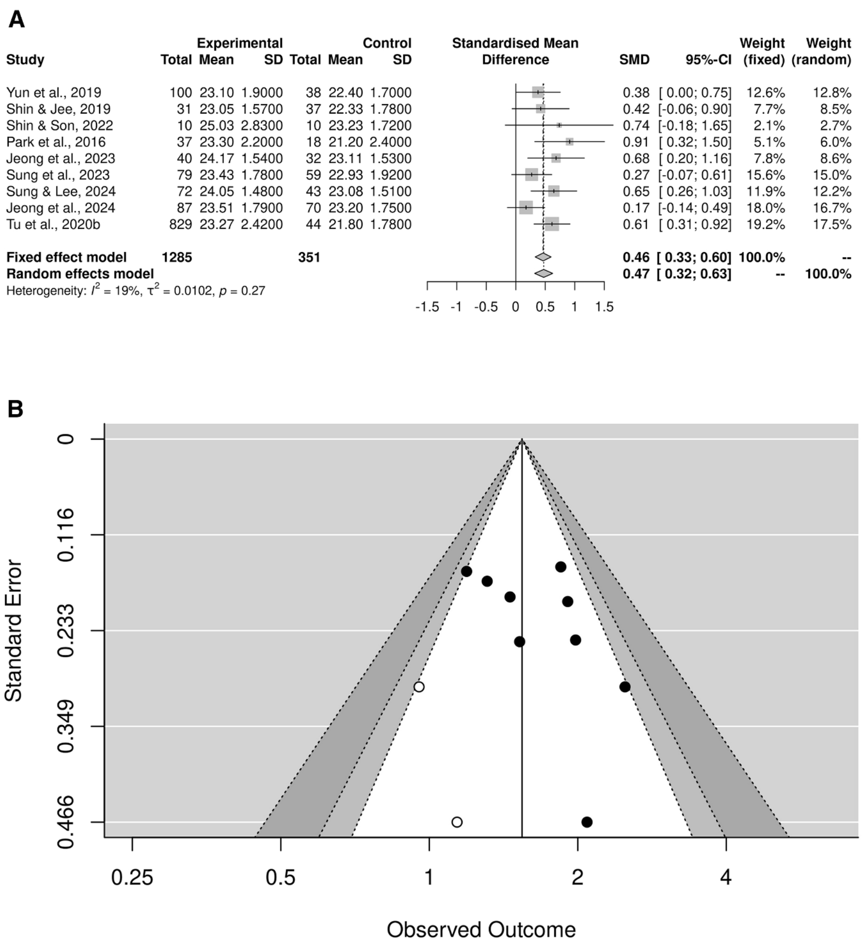

Figure 2. Body mass index (BMI) and G-test outcomes

(A) Forest plot of standardized mean differences (SMDs) for BMI between pass and fail groups. Pooled effects: fixed-effect SMD = 0.46 (95% CI 0.33–0.60) and random-effects SMD = 0.47 (95% CI 0.32–0.63); heterogeneity I^2 = 19% (τ^2 = 0.0102, p = 0.27).

(B) Funnel plot for assessment of small-study effects; open circles indicate trim-and-fill–imputed studies.

five variables (height, weight, BMI, muscle mass, and body fat). Meta-analysis showed no difference between the two groups in height (standardized mean difference (SMD), −0.08; 95% confidence interval (CI), −0.20–0.04; p = 0.40; I^2 = 4%) and body fat (SMD, 0.05; 95% CI, −0.17–0.26; p = 0.13; I^2 = 39%).

BMI

The analysis included nine studies.[7–9,11–16] The pass group had a lower BMI than the fail group (SMD, 0.47; 95% CI, 0.32–0.63; p = 0.27), and the heterogeneity was low (I^2 = 19%). The addition of two virtual studies with trim-and-fill showed that the SMD was 0.44 (95% CI, 0.28–0.59; $p < 0.001$; I^2 = 23.5%), showing no significant difference (Figures 2A and 2B).

Muscle mass

The analysis included seven studies.[7,8,11–15] The pass group had a higher muscle mass than the fail group (SMD, 0.31; 95% CI, 0.15–0.47; p = 0.96). There was no heterogeneity (I^2 = 0%), and no publication bias was found (Figures 3A and 3B).

Weight

The analysis included nine studies.[7,9–16] The pass group had a lower weight than the fail group (SMD, 0.26; 95% CI, 0.12–0.41; p = 0.18). Although the heterogeneity was low (I^2 = 29%), the addition of five hypothetical studies with trim-and-fill showed that the SMD was 0.09 (95% CI, −0.08–0.26; p = 0.30; I^2 = 61.7%), with no difference between the groups (Figures 4A and 4B).

Physical fitness meta-analysis

Data from the 3 km-running (SMD, −0.01; 95% CI, −0.38–0.36; p = 0.01; I^2 = 75%), push-up (SMD, 0.08; 95% CI, −0.10–0.26; p = 0.57; I^2 = 0%), and sit-up tests (SMD, 0.16; 95% CI, −0.04–0.36; p = 0.90; I^2 = 0%) all showed no difference between the pass and fail groups.

DISCUSSION

Various accelerated load (G-load) studies on animals have been conducted worldwide, but the amount of published data is small. Only about 20 reports of G-LOC animal experiments and a smaller number of human studies have been published. Since this is a military-related field, many studies have not yet been published, and given the 70–80-year history of the field, it appears to be very small compared to other disciplines.[17]

Gravity acceleration resistance can be affected by several factors, including the characteristics of the Gz environment. These include various physiological factors, such as the size and duration of the Gz, hypoxia, body composition, cardiovascular adaptation, dehydration, fatigue, and the effects of alcohol.[18] Among them, body composition is the most important and is a factor that humans can control, and several studies have shown it to affect gravitational acceleration resistance.[12–15]

Factors influencing body composition include skeletal muscle mass, body fat mass, and BMI. Skeletal muscle mass plays a role in preventing G-LOC by preventing the rapid concentration of blood in the lower extremities.[6] In this study, skeletal muscle mass showed a small effect size in the group that passed the G-test. In addition, high skeletal muscle mass supports the musculoskeletal system and helps prevent injuries[19] Air force pilots sit in a confined space flying military aircraft, and are exposed to high gravitational acceleration. Analysis has shown that the body is subjected to repeated shocks and stresses, with an increased risk of spinal damage, and an increase in flight

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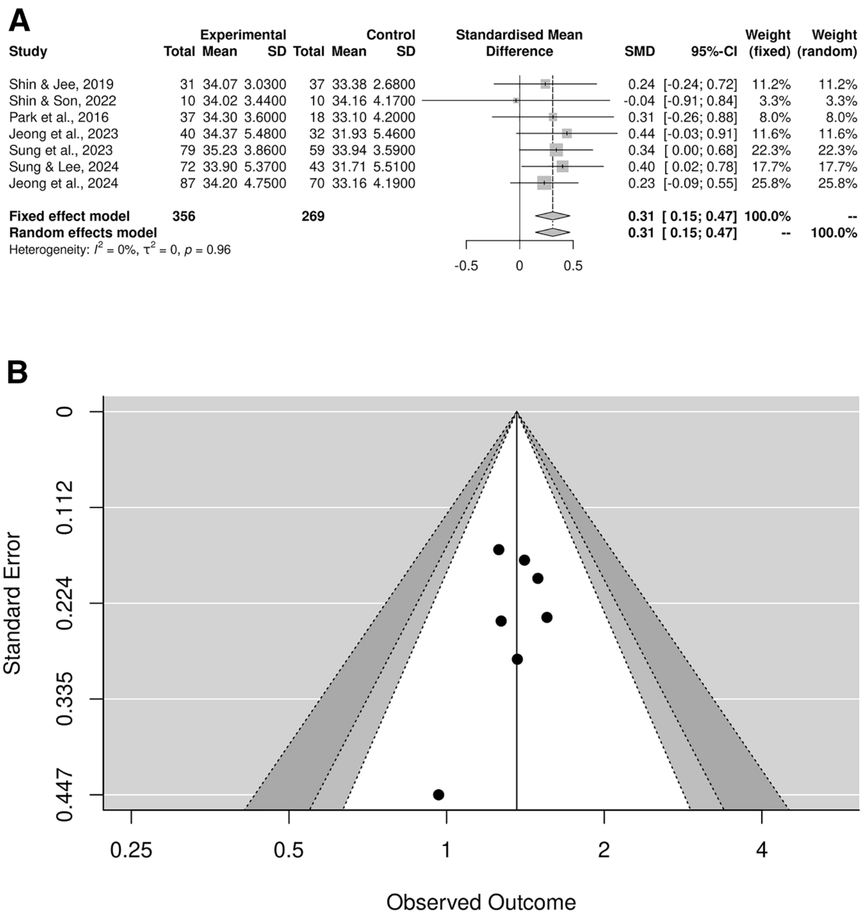

Figure 3. Skeletal muscle mass and G-test outcomes

(A) Forest plot of SMDs for muscle mass between pass and fail groups. Pooled effects: fixed-effect and random-effects SMD = 0.31 (95% CI 0.15–0.47); heterogeneity I^2 = 0% (p = 0.96).

(B) Funnel plot for assessment of small-study effects.

time has been reported as a major driver of acute cabin neck pain.[20] In addition, heavy pilot helmets with advanced equipment cause a variety of spinal diseases, and pilots flying fighter jets reported a higher prevalence of low back pain than pilots flying high-performance aircraft.[21]

The effectiveness of maintaining skeletal muscle does not stop at simply preventing musculoskeletal injuries. Maintaining muscle mass is strongly linked to physical strength and is directly linked to the body's immune system function. The immune system protects the body from infectious diseases by recognizing, attacking, and destroying foreign substances that enter the body.[22] The fighter pilot is stressed by the range of cognitive information and exposed to thermal stress caused by the fighter fuselage.[23] The pilot wears protective equipment to provide protection from stress, but the decrease in immunity due to stress acts as a threat to the pilot's health and life. When the body is exposed to a strong stressful environment, the secretion of cortisol is increased as an acute stress reaction,[24] and the G-test can also act as an extreme physical stressor, acutely activating the hypothalamic-pituitary-adrenal axis and increasing cortisol. Indeed, previous studies have shown that G-force acceleration exposure significantly increased cortisol secretion. Consistent with this evidence, a significant post-G-test rise in salivary cortisol in both the pass and fail groups, with a greater percentage increase observed in the fail group.[25] In addition to this, strong stress stimulation in the body can reduce IgA, thereby reducing overall immune tolerance.[26] In line with this immunological response, salivary IgA concentration decreased significantly after the G-test in both groups, with a larger reduction in the Fail group,[25] suggesting a transient suppression of mucosal immunity under acute high-G exposure.

As such, physical strength and body composition are very important factors. The Air Force Academy, which produces Korean Air Force officers, operates various fitness training programs to maintain and improve the physical strength of pilots and conducts physical fitness assessments every semester. The basic physical fitness assessment consists of 3 km of running, push-ups (2 min), and sit-ups (2 min). The physical fitness assessment consists of body composition measurement (skeletal muscle mass, body fat percentage), and the mission physical strength assessment consists of bench press, leg press, leg curl, lat pull-down, and arm curl.[27] By applying the results of this study, training programs can be refined to more effectively develop tolerance to gravitational acceleration by systematically targeting the body-composition and strength characteristics most closely associated with G-resistance. In practice, this would support a more individualized conditioning approach in which training loads, exercise selection, and progression are tailored according to each trainee's muscle mass, adiposity profile, and strength capacity, rather than relying solely on general aerobic- and calisthenics-based fitness standards. In addition, the physical fitness assessment framework and related coursework could be expanded to include more muscle-focused evaluations that better capture operationally relevant performance, such as one-repetition maximum testing, strength-to-body-mass indices, and joint-specific range-of-motion assessments. Integrating these measures alongside existing endurance, body composition, and mission-strength tests may improve the sensitivity of screening and monitoring, enable earlier identification of trainees who may require targeted intervention, and ultimately contribute to safer and more effective preparation for high-G flight environments.

A major strength of this study is the application of rigorous inclusion criteria, which reduced an initial pool of 184 studies to 10 that

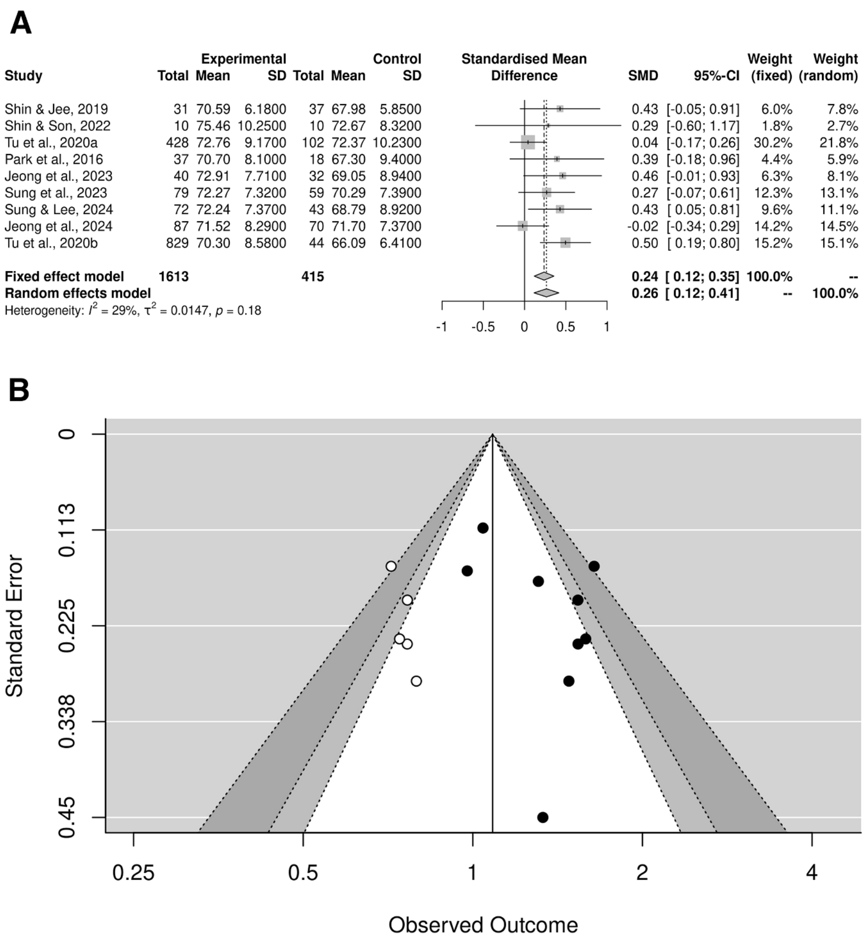

Figure 4. Body weight and G-test outcomes

(A) Forest plot of SMDs for body weight between pass and fail groups. Pooled effects: fixed-effect SMD = 0.24 (95% CI 0.12–0.35) and random-effects SMD = 0.26 (95% CI 0.12–0.41); heterogeneity I^2 = 29% (p = 0.18).

(B) Funnel plot for assessment of small-study effects; open circles indicate trim-and-fill–imputed studies.

appropriately addressed parameters related to body composition or the primary outcome of interest, G-LOC. Although the number of eligible studies was limited, the combined sample exceeded 2,100 participants, partially mitigating this constraint. To our knowledge, this is the first study to synthesize evidence linking exposure to gravitational acceleration with body composition and physical strength in pilots or prospective pilots. Nevertheless, the evidence base remains sparse, as only 10 G-LOC-related studies were identified over 10 years, and all included studies were conducted in Asian countries, limiting generalizability. Despite these limitations, the findings provide preliminary directions for incorporating body composition and strength factors into training and operational planning, with potential relevance not only for military aviation but also for future astronaut preparation.

Limitations of the study

This study is the first meta-analysis to synthesize evidence on the associations of body composition and physical fitness with G-test outcomes in Air Force pilot populations. However, the number of eligible studies was limited, partly because inclusion required pass/fail group comparisons with extractable mean and standard deviation data, which may have excluded studies without sufficient quantitative reporting. In addition, evidence was geographically concentrated in Asian countries (Korea and Taiwan), which may limit generalizability. Finally, methodological variability across studies could contribute to heterogeneity; therefore, we applied a random-effects model and reported reproducible statistical procedures using a single, consistently stated R version.

Conclusion

This study provides foundational evidence regarding the relationship between body composition and G-force resistance in Air Force pilot populations. Using a standardized meta-analytic framework, we identified that BMI, body weight, and muscle mass were associated with G-test outcomes, with weight and muscle mass demonstrating relatively small pooled effects. Collectively, these findings suggest that body-composition characteristics may contribute to G-tolerance and may be relevant to strategies aimed at reducing the risk of G-induced loss of consciousness (G-LOC). Nevertheless, interpretation should remain cautious due to the limited number of eligible publications and their geographic concentration. Future research should expand the evidence base using larger and more diverse cohorts and more standardized G-test and physical assessment protocols. In addition, mechanistic studies are warranted to clarify how body composition influences physiological performance under high +Gz conditions. Such efforts may inform the development of more effective conditioning programs and assessment frameworks, ultimately supporting pilot health and operational safety in future aerospace environments.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Jun-Young Sung (sjy7067@gmail.com).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- The dataset supporting the findings of this study is available from the corresponding author upon reasonable request.

- This study did not generate original code.
- No additional supporting items were generated.
- Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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AUTHOR CONTRIBUTIONS

Overall planning of the research, data acquisition, analysis, and interpretation, and major drafting and revision of manuscript submission were performed by L.L.K. and J.K.J Contributing to the data acquisition, analysis, and understanding were D.L.L. and Y.S.C Provision of the physiological and clinical opinion for conceptualization, overall organization, and direct supervision of the research were undertaken by J.Y.S. All authors have read and agreed to the published version of the manuscript.

DECLARATION OF INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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REFERENCES

1. Wallace, J.B., Newman, P.M., McGarvey, A., Osmotherly, P.G., Spratford, W., and Gabbett, T.J. (2021). Factors associated with neck pain in fighter aircrew: a systematic review and meta-analysis. Occup. Environ. Med. *78*, 900–912. https://doi.org/10.1136/oemed-2020-107103.
2. Sung, J.Y., Jeong, D.H., and Lee, K.L. (2024). Analysis of the relationship between body imbalance characteristics and physical ability in air force cadets: Physical function and gravity acceleration resistance. Sci. Rep. *14*, 19795. https://doi.org/10.1038/s41598-024-70531-2.
3. Slungaard, E., McLeod, J., Green, N.D.C., Kiran, A., Newham, D.J., and Harridge, S.D.R. (2017). Incidence of G-induced loss of consciousness and almost loss of consciousness in the Royal Air Force. Aerosp Med Hum Perfm *88*, 550–555. https://doi.org/10.3357/AMHP.4752.2017.
4. Cao, X.S., Wang, Y.C., Xu, L., Yang, C.B., Wang, B., Geng, J., Gao, Y., Wu, Y.H., Wang, X.Y., Zhang, S., and Sun, X.Q. (2012). Visual symptoms and G-induced loss of consciousness in 594 Chinese Air Force aircrew—a questionnaire survey. Mil. Med. *177*, 163–168. https://doi.org/10.7205/milmed-d-11-00003.
5. Ueda, K., Ogawa, Y., Yanagida, R., Aoki, K., and Iwasaki, K.-I. (2015). Dose-effect relationship between mild levels of hypergravity and autonomic circulatory regulation. Aerosp. Med. Hum. Perform. *86*, 535–540. https://doi.org/10.3357/AMHP.4162.2015.
6. Kim, I.K., Jeong, D.H., Sung, J.Y., and Kim, K.S. (2022). Analysis of G-test results according to fatigue, physical fitness and body composition of Air Force cadets using smart watches. Exerc. Sci. *31*, 98–104. https://doi.org/10.15857/ksep.2021.00563.
7. Shin, S., and Jee, H. (2019). ACTN-3 genotype, body composition, fitness, and +Gz tolerance in senior cadets. Aerosp. Med. Hum. Perform. *90*, 1055–1060. https://doi.org/10.3357/AMHP.5261.2019.
8. Yun, C., Oh, S., and Shin, Y.H. (2019). AGSM proficiency and depression are associated with success of high-G training in trainee pilots. Aerosp. Med. Hum. Perform. *90*, 613–617. https://doi.org/10.3357/AMHP.5323.2019.
9. Shin, S., and Son, S. (2022). Associations between ACE Genotypes, +8.5 Gz Tolerance, and Body Composition in F-15 Pilot Candidates. Mil. Med. *187*, 1248–1254. https://doi.org/10.1093/milmed/usab430.
10. Tu, M.Y., Chu, H., Lin, Y.J., Chiang, K.T., Chen, C.M., Chen, H.H., Yang, C.S., and Lai, C.Y. (2020). Combined effect of heart rate responses and the anti-G straining manoeuvre effectiveness on G tolerance in a human centrifuge. Sci. Rep. *10*, 21611. https://doi.org/10.1038/s41598-020-78687-3.
11. Park, J.S., Choi, J., Kim, J.W., Jeon, S.Y., and Kang, S. (2016). Effects of the optimal flexor/extensor ratio on G-tolerance. J. Phys. Ther. Sci. *28*, 2660–2665. https://doi.org/10.1589/jpts.28.2660.
12. Jeong, D.H., Lee, D.R., Lee, K.L., and Sung, J.Y. (2023). Gravitational acceleration test results according to functional movement screen and morphological symmetry results of air force cadets. Symmetry *15*, 804. https://doi.org/10.3390/sym15040804.
13. Sung, J.Y., Kim, I.K., and Jeong, D.H. (2023). Gravitational acceleration test results by lifestyle and physical fitness of Air Force cadets. Aerosp. Med. Hum. Perform. *94*, 384–388. https://doi.org/10.3357/AMHP.6155.2023.
14. Sung, J.Y., and Lee, K.L. (2024). Physical strength, body composition, and G-test results of air force cadets based on nutrition knowledge differences. Sci. Rep. *14*, 3083. https://doi.org/10.1038/s41598-024-53600-4.
15. Jeong, D., Lee, E., Sung, J., and Kang, S. (2024). Relationship between sleep quality and gravitational Tolerance. Sleep Breath. *28*, 1223–1229. https://doi.org/10.1007/s11325-023-02987-x.
16. Tu, M.Y., Chu, H., Chen, H.H., Chiang, K.T., Hu, J.M., Li, F.L., Yang, C.S., Cheng, C.C., and Lai, C.Y. (2020). Roles of physiological responses and anthropometric factors on the gravitational force tolerance for occupational hypergravity exposure. Int. J. Environ. Res. Publ. Health *17*, 8061. https://doi.org/10.1007/s12576-016-0461-4.
17. Nishida, Y., Maruyama, S., Shouji, I., Kemuriyama, T., Tashiro, A., Ohta, H., Hagisawa, K., Hiruma, M., and Yokoe, H. (2016). Effects and biological limitations of +Gz acceleration on the autonomic functions-related circulation in rats. J. Physiol. Sci. *66*, 447–462. https://doi.org/10.1007/s12576-016-0461-4.
18. Newman, D.G. (2015). High G Flight: Physiological Effects and Countermeasures (Ashgate Publishing).
19. Rausch, M., Weber, F., Kühn, S., Ledderhos, C., Zinner, C., and Sperlich, B. (2021). The effects of 12 weeks of functional strength training on muscle strength, volume and activity upon exposure to elevated G z forces in high-performance aircraft personnel. Milit. Med. Res. *8*, 15. https://doi.org/10.1186/s40779-021-00305-8.
20. Honkanen, T., Sovelius, R., Mäntysaari, M., Kyröläinen, H., Avela, J., and Leino, T.K. (2018). +Gz Exposure and spinal injury-induced flight duty limitations. Aerosp. Med. Hum. Perform. *89*, 552–556. https://doi.org/10.3357/amhp.4999.2018.

21. Honkanen, T., Kyröläinen, H., Avela, J., and Mäntysaari, M. (2017). Functional test measures as risk indicators for low back pain among fixed-wing military pilots. J. Roy. Army Med. Corps *163*, 31–34. https://doi.org/10.1136/jramc-2015-000510.

22. Drummond, L.R., Campos, H.O., Drummond, F.R., de Oliveira, G.M., Fernandes, J.G.R.P., Amorim, R.P., da Costa Monteiro, M., Lara, H.F.G., Leite, L.H.R., and Coimbra, C.C. (2022). Acute and chronic effects of physical exercise on IgA and IgG levels and susceptibility to upper respiratory tract infections: a systematic review and meta-analysis. Pflügers Archiv *474*, 1221–1248. https://doi.org/10.1007/s00424-022-02760-1.

23. McMahon, T.W., and Newman, D.G. (2016). G-induced visual symptoms in a military helicopter pilot. Mil. Med. *181*, e1696–e1699. https://doi.org/10.7205/milmed-d-16-00073.

24. Hackney, A.C., and Walz, E.A. (2013). Hormonal adaptation and the stress of exercise training: the role of glucocorticoids. Trends Sport Sci. *20*, 165–171.

25. Lee, M.J., Yoon, S., Kim, I.K., and Sung, J.Y. (2025). Effects of Gravitational Acceleration on Physical Fitness, Stress, and Immunity Levels of Prospective Air Force Pilots. Stress Health *41*, e70060. https://doi.org/10.1002/smi.70060.

26. Whitney, C., Hatch-McChesney, A., Allen, J., Hennigar, S., McClung, J., Pasiakos, S., and Smith, T. (2021). Effects of energy deficit on secretory IgA during a simulated multi-stressor military operation. Curr. Dev. Nutr. *5*, 1143. https://doi.org/10.1093/cdn/nzab061_027.

27. Republic of Korea Air Force Academy (2024). Education Guide for Cadets.

28. Wells, G.A., Shea, B., O'Connell, D., Peterson, J., Welch, V., Losos, M., and Tugwell, P. (2000). The Newcastle-Ottawa Scale (NOS) for Assessing the Quality of Nonrandomised Studies in Meta-Analyses (Ottawa Hospital Research Institute).

29. Herzog, R., Álvarez-Pasquin, M.J., Díaz, C., Del Barrio, J.L., Estrada, J.M., and Gil, Á. (2013). Are healthcare workers' intentions to vaccinate related to their knowledge, beliefs and attitudes? A systematic review. BMC Public Health *13*, 1–17. https://doi.org/10.1186/1471-2458-13-154.

30. Higgins, J.P.T., Thompson, S.G., Deeks, J.J., and Altman, D.G. (2003). Measuring inconsistency in meta-analyses. Br. Med. J. *327*, 557–560. https://doi.org/10.1136/bmj.327.7414.557.

31. Stroup, D.F., Berlin, J.A., Morton, S.C., Olkin, I., Williamson, G.D., Rennie, D., Moher, D., Becker, B.J., Sipe, T.A., and Thacker, S.B. (2000). Meta-analysis of observational studies in epidemiology: A proposal for reporting. JAMA *283*, 2008–2012. https://doi.org/10.1001/jama.283.15.2008.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Biological samples		
Human participants: Male fighter pilots or prospective pilots aged 20 years or older	Republic of Kore Taiwan	N/A N/A
Software and algorithms		
Statistical software: R	R Foundation for Statistical Computing	version 4.3.4
Other		
G-test gravitational acceleration system	Republic of Kore Taiwan	N/A N/A

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Participants were male fighter pilots or prospective pilots aged 20 years or older who were required to tolerate gravitational acceleration. Although the literature search covered studies conducted worldwide, only Asian populations were included in the final analysis because results from other populations did not show sufficient consistency with the present research framework.

Ethics approval and consent to participate

All the authors were well informed of the WMA Declaration of Helsinki Ethical Principles for Medical Research Involving Human Subjects and confirmed that this study firmly fulfilled the Declaration.

METHOD DETAILS

Search strategy and selection criteria

This study searched for papers published in the past 10 years (2014 to September 2024). No language restrictions were applied to capture a broad range of evidence. We also attempted to identify gray literature and relevant prior reviews. The primary searches were conducted in PubMed and ScienceDirect, and Google Scholar was used as a supplementary academic search engine to screen additional potentially relevant records. Gray literature screening included theses, conference materials, and reports where identifiable. The searches were conducted between January 2, 2025 and April 30, 2025. Inclusion criteria were: (1) pilots or pilot trainees undergoing a G-tolerance (G-test), (2) outcomes reported as pass/fail, and (3) extractable mean and SD data. Studies without a G-test, without pass/fail grouping, or without sufficient quantitative data were excluded. The search terms used were: PubMed: (“pilots”[Mesh]) AND “gravitation”[Mesh]) AND “body composition”[Mesh]) OR “Physical Fitness”[Mesh]); Science Direct: (“Pilot” AND “gravitation” AND “G-test” AND “Body Composition” OR “physical fitness”); and Google Scholar: (“pilots” OR “air force pilot” OR “reserve pilot” OR “cadet” OR “aircrew” AND “gravitation” OR “G force” OR “G-tolerance” OR “G-test” AND “body composition” OR “body height” OR “body weight” OR “body mass index” OR “muscle mass” OR “body fat” OR “Physical fitness”).

Three reviewers independently reviewed this search (K.L.L., K.J.J., & J.Y.S.) to evaluate eligibility, and disagreements were resolved through discussions and consultations with other authors (D.R.L. & Y.S.C.) (Figure 2).

Data extraction

Two reviewers (K.L.L. & K.J. J.) independently extracted data from the included studies using Excel 2020, and disagreements were resolved through discussions with other authors (D.R.L. & Y.S.C.). The extracted references were managed by EndNote; the data that were collected included the authors, publication year, country, number of samples (pass/fail group), average age, sex, body composition, and physical fitness.

Assessment of risk of bias

Three reviewers (K.L.L., K.J.J., & J.Y.S.) independently performed bias risk assessments using the Newcastle-Ottawa Scale (NOS).[28,29] The NOS assesses the quality of the three key aspects of the included study: (1) selection, (2) comparability, and (3) exposure. The maximum score was 10 points, and the quality of the study was assessed as poor when the score was 0–4 points, poor when the score was 5–6, good when the score was 7–8, and very good when the score was 9–10 points. Discrepancies in quality assessments were resolved through discussions with other authors (D.R.L. & Y.S.C.).

QUANTIFICATION AND STATISTICAL ANALYSIS

Meta-analysis procedures, including effect size calculation, homogeneity/heterogeneity assessment, subgroup (sub-variable) analyses, and publication bias analyses, were conducted in R (version 4.3.4; R Foundation for Statistical Computing, Vienna, Austria) using the metafor and meta packages. Random-effects models with inverse-variance weighting were used as the primary analytic approach, and fixed-effect estimates were additionally computed for comparison. The effect size was calculated using Hedges' method (Hedges' g), and the average effect size was calculated by assigning weights reflecting the characteristics of each study. SMDs were calculated as pass minus fail; positive values indicate higher values in the pass group. Interdisciplinary variance was estimated using Cochran's Q and I^2 indices, and values of 25%, 50%, and 75% for the I^2 indices were considered to represent low, moderate, and high levels of heterogeneity, respectively.[30] Finally, we evaluated the degree of potential publication bias with a funnel plot, which visually confirms symmetry, and used the trim-and-fill method to increase the reliability of the study.

ADDITIONAL RESOURCES

This systematic review and meta-analysis was registered in PROSPERO (CRD42025644100) and was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[31]