



Impact of yoga training on heart rate variability and pilot performance: a randomized controlled trial

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Abstract

Background Piloting military aircraft demands precise execution of maneuvers under high-stress conditions. Yoga has been proposed as a potential intervention to enhance stress management, operational performance, and flight safety in pilots. However, its effects on stress resilience and performance metrics need further investigation.

Methods In this randomized controlled trial, 18 pilots were randomly assigned to either a Yoga intervention group ($n = 10$) or a control group ($n = 8$). Heart rate variability (HRV) measures were analyzed to evaluate physiological stress responses. Performance variables, including completion times for flight maneuvers and number of errors during emergency protocol, were also assessed before and after a 12-week intervention period.

Results HRV analysis showed improvements in stress resilience, indicated by changes in heart rate variability (HRV) parameters such as standard deviation of NN intervals (SDNN), root mean square of successive differences (RMSSD), low frequency (LF), and high frequency (HF). The Wilcoxon rank test revealed significant results regarding performance variables within the Yoga group, particularly for the Touch & Go maneuver ($p = 0.016$) and the emergency maneuver ($p = 0.039$), with large effect sizes (0.9444 and 0.8333, respectively). While completion times were longer for the Yoga group, indicating a more careful approach, the number of errors significantly decreased ($p = 0.025$, effect size = 0.917), with a notable reduction observed in the Yoga group compared to controls.

Conclusion Incorporating yoga into pilot training protocols holds promise for better executive/cognitive functions, enhancing stress management and operational performance, reducing the number of errors, and leading to increased flight safety. While yoga may lead to longer completion times for maneuvers, the significant reduction in errors and improvements in stress resilience highlight its potential benefits. However, careful consideration is needed to balance improved precision with operational efficiency.

Keywords Yoga · Air force · Military aviation · Pilot training · Heart rate variability · Pilot performance

Introduction

Military aviation pilots represent a distinct and high-demand occupational group, routinely exposed to intense psychophysiological stress, as demonstrated by heart rate variability studies using portable biosensors in real flight or simulated operational contexts [1–3]. They undergo rigorous training regimens and face numerous stressors both in training and during actual missions [4–8]. These stressors can range from physical demands to cognitive and emotional pressures, all of which can impact their overall performance and well-being [9–11]. Physically, pilots endure high G-forces and muscular strain, which can elevate heart rate and cortisol levels, as observed during simulated and real combat maneuvers [10]. Cognitively, they must maintain attention, execute

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rapid decision-making, and manage multitasking under time pressure—factors linked to increased sympathetic nervous system activation and reduced heart rate variability [9]. Emotionally, they are exposed to unpredictable and life-threatening scenarios that induce acute stress responses, including heightened electrodermal activity and elevated anxiety levels, as seen in air accident simulations and urban combat contexts [9, 11]. Military aviation pilots often experience high levels of stress due to the nature of their work, which can affect their physiological responses and, consequently, their performance during critical tasks [1–11].

Stress among military aviation pilots encompasses various psychological, physiological, and environmental factors; these factors can include the demands of combat missions, long hours of training, exposure to high-risk situations, and the need for split-second decision-making [9, 12]. In this context, stress refers to the body's response to these demanding situations, which can manifest as heightened arousal, increased heart rate, elevated levels of stress hormones like cortisol, and cognitive challenges such as impaired decision-making and attentional focus [13–18]. Chronic stress in military aviation pilots can have significant detrimental effects on physical and mental health, potentially leading to fatigue, burnout, decreased resilience, and impaired performance during critical tasks [9, 12–18].

HRV is a psychophysiological measure that reflects the variation in the time intervals between consecutive heartbeats, regulated by the autonomic nervous system, which controls involuntary bodily functions such as heart rate, respiration, and digestion [19–21]. It is interpreted using both classical standards and updated methodological frameworks [21, 22]. HRV is considered an indicator of autonomic flexibility and adaptability, with higher HRV generally associated with better health outcomes and increased resilience to stress [23–25]. In the context of military aviation, HRV is particularly relevant as it reflects the balance between sympathetic (fight or flight) and parasympathetic (rest and digest) nervous system activity and is especially relevant in aviation psychology because it provides a non-invasive and sensitive index of autonomic nervous system balance and reactivity, allowing the detection of stress, workload, and adaptive capacity in high-demand operational environments such as those encountered by military pilots [19–25]. Reduced HRV is often observed under conditions of chronic stress, possibly indicating decreased autonomic flexibility and impaired physiological recovery. It potentially predisposes pilots to performance decrements, fatigue, and increased susceptibility to stress-related health issues [19–25].

Performance in military aviation encompasses a range of skills and competencies essential for completing mission objectives effectively and efficiently while ensuring safety and resource conservation [26, 27]. Key performance metrics for military aviation pilots include accuracy, speed,

precision, decision-making under pressure, situational awareness, and adaptability to changing environments [28, 29]. The ultimate goal is to complete mission tasks with the highest level of efficiency, minimizing the time required to achieve objectives while conserving fuel, ammunition, and other resources [30, 31]. Efficient performance is critical not only for mission success but also for ensuring the safety of personnel and equipment; therefore, performance in military aviation is characterized by the ability to execute tasks swiftly, accurately, and safely, even in high-stress and dynamic operational environments [25–31].

Portuguese military aviation pilots face unique challenges in their operational roles, compounded by the absence of a documented, structured training regimen [32–34]. Unlike some other military branches where training programs are standardized and regimented, Portuguese military pilots are tasked with maintaining their physical fitness and readiness largely on their own initiative, with the primary objective of passing yearly physical exams [32–34]. This lack of a standardized training program presents an opportunity to explore interventions that could enhance pilots' physical and mental well-being and optimize their performance in the absence of formal guidance [32].

Given the demanding nature of military aviation duties and the inherent stressors associated with operational missions, there is growing recognition of the importance of implementing strategies to support pilots' overall health and resilience [1–12, 32–34]. Yoga, with its multifaceted approach encompassing physical postures, breathing techniques, and mindfulness practices, has demonstrated efficacy in reducing stress, improving physiological markers such as heart rate variability (HRV), and enhancing overall well-being in diverse populations [35–42]. Unlike traditional physical fitness programs, which often target only cardiovascular or muscular endurance [43, 44], or cognitive-behavioral strategies that focus predominantly on psychological coping [45], yoga simultaneously engages physical, autonomic, and psychological domains. This integrative benefit is particularly valuable in high-demand operational environments such as military aviation, where optimal performance depends on the interplay of physical readiness, stress regulation, and cognitive clarity [32, 35, 40, 42]. Therefore, there is a compelling rationale for conducting a randomized controlled trial (RCT) to investigate whether integrating yoga into the training regimen of Portuguese military pilots could serve as a viable strategy for managing stress, enhancing resilience, and optimizing performance in their unique operational context [32–42].

Furthermore, the findings from this RCT will provide valuable insights into the potential benefits of incorporating yoga or other structured training components into a future mandatory training regimen program for Portuguese military pilots. By identifying effective interventions that promote physical and mental fitness, as well as operational readiness, the study

aims to contribute to the development of evidence-based practices that can support the health and performance goals of military aviation personnel in Portugal and potentially inform training protocols in similar contexts worldwide.

The primary objective of this randomized controlled trial (RCT) is to evaluate the efficacy of incorporating a structured yoga program into the training regimen of military aviation pilots. Specifically, the aim is to determine whether yoga can effectively:

1. Enhance stress resilience,
2. Improve heart rate variability (HRV), and
3. Optimize overall operational performance.

It is hypothesized that participation in the yoga intervention will result in

- Significant improvements in stress resilience (as measured by validated psychometric tools and physiological markers).
- Improvements in HRV parameters, indicating enhanced autonomic balance.
- Increased autonomic adaptability to operational stressors.
- Enhancements in cognitive and psychomotor performance (e.g., attention, reaction time, working memory).
- Future translation of these psychophysiological and cognitive benefits into improved operational effectiveness during simulated and real flight missions.

Materials and methods

Sample

In Portugal, the Tirocinium represents the culminating phase of military aviation training, giving pilots the title of “Master in Military Aeronautics: Aviator Pilot Specialization,” conducted at Base Aérea Nº11 in Beja, within Esquadra 101. Spanning a duration of 10 months, it comprises 18 days of theoretical instruction complemented by 185 days of practical training. This practical component includes 177 h of in-aircraft instruction, augmented by 33 h spent in a stationary flight simulator. Collectively, each pilot undergoes a rigorous program amounting to 180 flight hours, equipping them with the necessary skills and experience essential for operational readiness and proficiency in their military aviation roles. All pilots enrolled in the course, classes of 2021 and 2022, at the Portuguese Air Force Academy participated in this research. The sample size was determined using OpenEpi, version 3, based on the following equation:

$$\text{Sample size } n = \left[\text{DEFF} * Np(1 - p) \right] / \left[(d2/Z21) - \alpha/2 * (N - 1) + p * (1 - p) \right].$$

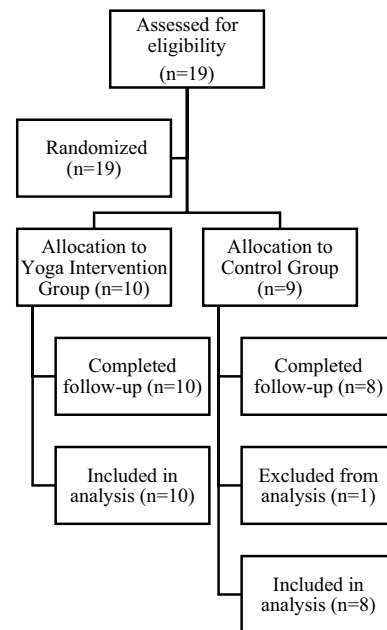


Fig. 1 Participant flow diagram where

- Population size (N): 19
- Hypothesized % frequency of outcome factor in the population (p): 50% ± 5%
- Confidence limits as % of 100 (absolute ± %) (d): 5%
- Design effect (DEFF): 1
- For a confidence level of 90% to 95%, the sample size required was 18.

Eighteen professional military pilots from the Portuguese Air Force participated in this control case report study (characteristics of military pilots in Table 1 of the supplementary material). Procedures were approved by the Évora University research ethics committee (approval number: 21050) and participants gave written informed consent according to the Helsinki declaration. The study was registered on 19th April 2023 on ClinicalTrials.gov under the identifier NCT05821270.

The study’s participant flow, detailed in Fig. 1 and adhered to CONSORT guidelines [46], included 19 pilots assessed for eligibility with none being excluded for factors such as prior experience with yoga, medical issues, or HRV abnormalities. All 19 were randomized using random.org. Ten pilots were assigned to the Yoga Intervention Group and nine to the Control Group, with all participants receiving their respective interventions. Both groups had complete follow-up, and

one participant was excluded from the analysis, for lifestyle changes (namely ceasing smoking), in the 12-week period.

Intervention

Over a period of 12 weeks, the Control Group ($n = 8$) attended the protocolized classes of the “Masters in Military Aeronautics: Aviator Pilot Specialist” course. In contrast, the Yoga Intervention Group ($n = 10$) participated in the same course along with two additional yoga classes per week, each lasting 1 h. Sessions were consistent across participants—two 60-min classes per week with identical structure and progression tailored to pilot needs to address both perceived challenges faced by pilots, as well as those identified in the literature research [32]. In addition, participants were instructed to maintain their usual routines throughout the intervention period. Potential confounding variables—such as diet, sleep patterns, and work schedules—were inherently controlled, as the pilots resided on the airbase during the Tirotinium phase and were subject to continuous monitoring and regulation by the Portuguese Air Force Academy. A 12-week Ashtanga-Vinyasa Yoga Supta Method (AVYSM) was used, combining flowing posture sequences (vinyasas), breath synchronization, and “supta” (closed-eyes) practice. All sessions were delivered by a certified Ashtanga-Vinyasa Yoga instructor expert with over 300 h of training and approximately 10 years of teaching experience [32].

Viniyoga emphasizes adapting yoga practices to the individual’s health, lifestyle, and physiological needs. This approach allows to modify class intensity, sequence, and

breath techniques to match pilots’ fitness levels and stress profiles. Compared to gentler styles (e.g., Hatha or Iyengar), this modality’s moderate intensity, structured breath flow, and progressive challenge align better with military pilots’ physiological demands and readiness needs, ensuring both safety and relevance. This specific method offers a balanced integration of movement, breath, sensory adaptation, and adaptability—essential for meeting the complex demands of military aviation contexts [47].

Data collection

Pilots completed a 30-min scenario encompassing visual and instrument flight conditions in a flight simulator currently in use for pilot training in the Portuguese Airforce Academy (Epsilon—SEPS TB30, in Fig. 2). All flight maneuvers followed a predetermined sequence with randomized emergency activation times. Action durations were timed using a chronometer (Huawei P20Pro stopwatch app), as smartphone timing apps have been shown to be highly accurate and reliable, often achieving excellent correlations with gold-standard equipment like timing gates, along with excellent test–retest reliability [48]. Performance feedback was provided by the flight simulator controller, based on protocol adherence (Figs. 3 and 4 in the supplementary material). Autonomic modulation was measured with HRV in basal conditions (3 min) with the pilots sitting inside the simulator cabin immediately prior to the simulation maneuvers, during the simulation maneuvers, as well as immediately after the simulation maneuvers (3 min). Operative performance

Fig. 2 Left, the inside of the cockpit for the flight simulator Epsilon TB30 and a pilot ready to start the protocol; right, the inside of the control room and the setup device of the flight simulator operator



was measured during the flight simulation maneuvers. Participants refrained from consuming substances affecting the nervous system 24 h before the protocol—regular intake of prescribed medication and caffeine was maintained throughout the intervention period; the use of any other substances is strictly prohibited within the airbase, with the Portuguese Air Force Academy enforcing compliance and monitoring for any unauthorized substance use.

All pilots are equipped with a manual including a protocol for resolving flight emergencies, which may be accessed either in a physical book form or on a tablet as shown in Fig. 2. This protocol is used both in the simulator and during real flights, containing mandatory step-by-step instructions organized by type of emergency.

The autonomic response of pilots was evaluated during different maneuvers: Habituation (H), First Take-off (FTO), First Flight (FF), Touch & Go maneuver (composed of First Landing (FL) and Second Take-off (STO) maneuvers), Second Flight (SF), Emergency (E) composed of an alternator failure (the emergency is activated by the simulator controller leading to the emergency protocol response actions), and Recovery (R).

Heart rate monitor Polar H10 [23, 49] was used to measure HRV. Different HRV variables were extracted in the time domain, frequency domain, and non-linear measures. In the time domain, mean heart rate (HR), RR intervals, standard deviation of all normal-to-normal RR intervals (SDNN), and root mean square of successive differences RR interval differences (RMSSD) were extracted [42, 49]. In the frequency domain, the low frequency (LF) (ms²), the high frequency (HF) (ms²), and the total power were calculated [50, 51]. Lastly, non-linear measures, such as RR variability from heartbeat to short-term Poincaré graph (width) (SD1), RR variability from heartbeat to long-term Poincaré graph (length) (SD2), Stress Index (SI—representing the degree of load on the autonomic nervous system), SNS INDEX (Sympathetic Nervous System Index), and PNS INDEX (Parasympathetic Nervous System Index) were also obtained [50–52]. Kubios HRV software was used to process HRV signals [53].

Performance was also assessed by the number of errors made by the pilot while following the mandatory emergency protocol established by the Portuguese Air Force. Failing to perform a step or performing it incorrectly was recorded as a performance error. The two variables used for this study were the time to solve the emergency (in minutes) and the number of errors made by the pilot (including not performing or incorrectly performing the steps of the emergency protocol).

Data analysis

Descriptive statistics for both the intervention and control groups were then generated using Jamovi (Desktop version 2.3.16). Normality was assessed using the Shapiro–Wilk test, with *p*-values greater than 0.05 indicating normal distribution, while *p*-values less than or equal to 0.05 suggested non-normal distribution [54–56].

In addition, we conducted *T*-Tests (Student's *t*) for paired samples and calculated effect sizes (Cohen's *d*) for normally distributed data. For non-normally distributed data, we employed the Wilcoxon rank test (Wilcoxon *W*), a common nonparametric alternative that can be used to compare the medians of two independent groups, and computed effect sizes using Rank Biserial Correlation. In both cases, significant values typically fall below the conventional threshold of 0.05 [54–56].

Results

The aim of this research was to analyze the effect of a 12-week yoga program [32] on the autonomic response and operative performance of professional military aviation pilots in a flight simulator emergency.

The Shapiro–Wilk test showcased *p*-values less than or equal to 0.05, suggesting non-normal distribution [54–56] for the HRV variables showcased in Tables 2 (time domain), 3 (frequency domain) and 4 (non-linear variables) in the appendix.

Regarding performance, the habituation and recovery periods, each lasting 3 min, were excluded from the performance times in this study since all pilots had to wait for these 3 min in the simulator cabin at the simulator controller's request, so it did not impact the internal consistency of timing data. In addition, to avoid bias, we asked the pilots not to share information about the simulation exercises with their colleagues, enforced by the Airforce study coordinator. Moreover, as a redundancy measure, the duration of the second flight before the emergency activation was random and controlled by the simulator controller. This random waiting time was not included in the performance time. The performance time considered in this study was the period from the activation of the emergency until its resolution.

Performance was also assessed by the number of errors made by the pilot while following a mandatory emergency protocol established by the Portuguese Air Force. This protocol is used both in the simulator and during real flights, provided to pilots in the form of a tablet or notebook containing step-by-step instructions. Failing to perform a step or performing it incorrectly was recorded as a performance error. In addition, the Epsilon-TB30 simulator shuts down automatically for any pilot, in scenarios in which their life is

at risk or scenarios in which the damage to the aircraft is too severe, failing the flight simulation scenario and ending the evaluation with it being considered a failure (a binary failure outcome), which did not occur for any pilot in this study.

The Shapiro–Wilk test indicated p -values less than or equal to 0.05, suggesting non-normal distribution [54–56] for the performance variables showcased in Tables 5 (performance variables in minutes during different flight moments) and 6 (performance variables in Number of Errors (NE) during the flight emergency) in the appendix.

Wilcoxon rank test (Wilcoxon W , Table 7 in the appendix for HRV variables; Table 8 in the appendix for Performance variables in minutes; Table 9 in the appendix for Performance variables in number of errors) showcased significant results after the 12-week period:

1. Within the Yoga group regarding HRV time domain variables:
2. Mean HR (0.049) with a large negative effect size (-0.7090) during habituation;
3. RMSSD (0.020) with a large positive effect size (0.8182) during the second flight;
4. SDNN (0.049) with a large negative effect size (-0.7091) during the first takeoff;
5. SDNN (0.049) with a large positive effect size (0.7091) during the first landing.
6. Within the Yoga group regarding HRV frequency domain variables:
7. LF (0.049) with a large negative effect size (-0.7091) during the second flight;
8. HF (0.049) with a large positive effect size (0.7091) during the second flight;
9. Within the Yoga group regarding HRV non-linear variables:
10. SD1% (0.014) with a large positive effect size (0.855) during habituation;
11. SD1% (0.004) with a large positive effect size (0.964) during the first flight;
12. SD1% (0.006) with a large positive effect size (0.927) during the first landing;
13. SD1% (0.004) with a large positive effect size (0.964) during the second takeoff;
14. SD1% (0.004) with a large positive effect size (0.964) during the second flight;
15. SD1% (0.004) with a large positive effect size (0.964) during the emergency;
16. SD1% (0.014) with a large positive effect size (0.855) during recovery;
17. SD2% (0.002) with a large negative effect size (-1.000) during the first takeoff;
18. SNS Index (0.049) with a large negative effect size (-0.7091) during the first flight;
19. SNS Index (0.014) with a large negative effect size (-0.8545) during the first landing;
20. SNS Index (0.004) with a large negative effect size (-0.9636) during the second takeoff;
21. SNS Index (0.049) with a large negative effect size (-0.7091) during the emergency;
22. SNS Index (0.049) with a large negative effect size (-0.7091) during recovery.
23. Within the Control group, regarding HRV non-linear variables:
24. SD2% (0.016) with a large negative effect size (-0.944) during the first takeoff.
25. Between groups, regarding HRV non-linear variables:
26. SI (0.023) with a large negative effect size (-0.8889) during the first landing.
27. Within the Yoga group, regarding performance variables (in minutes):
28. Touch & Go maneuver ($p=0.016$) with a large effect size (0.9444) and between groups regarding the emergency maneuver ($p=0.039$) with a large effect size (0.8333).
29. Between groups, regarding performance variables (in number of errors)
30. Number of errors ($p=0.025$) with a large effect size (0.917).

Discussion

In our study, various HRV metrics were examined across different flight conditions, and most differences were found within the Yoga group, all of them being positive:

- During habituation, the mean HR of the Yoga group showed a significant reduction ($p=0.049$) with a large negative effect size (-0.7090), indicating a decrease in heart rate, reflecting lower stress levels in anticipation of the tasks ahead [1, 22, 23, 49].
- The RMSSD during the second flight increased significantly for the Yoga group ($p=0.020$) with a large positive effect size (0.8182), suggesting improved parasympathetic activity and autonomic balance [4, 22, 49, 51].
- HF increased significantly ($p=0.049$, effect size 0.7091) during the second flight, reflecting enhanced parasympathetic activity [2, 22, 49, 51].
- Notably, SD1% exhibited large positive effect sizes across multiple conditions, including habituation ($p=0.014$, effect size 0.855), first flight ($p=0.004$, effect size 0.964), and recovery ($p=0.014$, effect size 0.855), indicating a significant improvement in short-term heart rate variability and autonomic responsiveness, suggesting enhanced parasympathetic activity and better stress resilience during these phases: this is interpreted as an

improvement in vagal tone, which is associated with a calm-yet-ready physiological state with the autonomic nervous system being able to flexibly respond to and recover from acute stressors [2, 22, 48–50].

- Both LF and SDNN showed significant decreases ($p=0.049$, effect size -0.7091) during the second flight and first takeoff, respectively, indicating reduced overall HRV and autonomic flexibility under stress, highlighting consistent improvements in short-term HRV and autonomic responsiveness [5, 22, 28, 42, 49].
- The SNS Index also showed significant reductions, including the first flight ($p=0.049$, effect size -0.7091) and recovery ($p=0.049$, effect size -0.7091), indicating a decrease in sympathetic nervous system activity and reduced stress levels [7, 12, 22, 50–52].

The findings within the intervention group align with previous literature on the effects of yoga practice on cardiac parasympathetic nervous modulation among healthy yoga practitioners [57], as well as on heart rate variability in general [58].

Regarding the differences found within the control group, the significant reduction in SD2% with a large negative effect size ($p=0.016$, effect size -0.944), which reflects long-term HRV, suggests that the control group experienced a marked decrease in autonomic flexibility [22, 24, 26, 50–52] during the initial phase of the flight. The negative effect size indicates a decline in the variability of heart rate intervals, pointing to a potential increase in stress or a diminished capacity for autonomic regulation under the high-demand conditions of takeoff [50–52]. While longitudinal data and multimodal stress markers would be necessary to confirm this relationship between reduced autonomic flexibility and cumulative stress or the absence of intervention, this finding highlights the potential protective role of interventions like AVYS in maintaining long-term HRV stability under operational stress.

The Wilcoxon rank test (Wilcoxon W) also showcased significant results between groups after the 12-week period for the Stress Index (SI) ($p=0.023$), during the first landing, with a substantial negative effect size (-0.8889). This significant reduction in SI, which reflects the balance between stress-related physiological responses, indicates that the Yoga group experienced a notable decrease in stress levels compared to the control group during the first landing phase with the negative effect size suggesting a considerable decline in stress response [11, 22, 27, 50–52]. While the yoga intervention may have buffered the autonomic stress response during landing, there are limitations of short-term HRV analysis that should in future studies be supported by replication or multimodal stress indicators (e.g., cortisol analysis).

No differences were found within or between groups during the emergency phase, likely due to all pilots being uniformly trained to follow the same protocol, resulting in uniformly high-stress levels and attention requirements for timely and correct execution. However, the variable POWER demonstrated a trend towards significance ($p=0.084$, effect size 0.636) for the Yoga group. This finding suggests that with a longer intervention period, yoga might potentially enhance the pilots' HRV, indicating a possible discovery of improved autonomic regulation and stress resilience [50, 52] in future, longer studies. The moderate effect size further supports the potential of yoga as a beneficial practice for improving physiological and performance outcomes in high-stress environments like military aviation emergencies [50, 52].

These findings suggest that specific flight conditions significantly influence autonomic modulation and stress responses, with potential implications for optimizing pilot performance and well-being. The results highlight the effectiveness of the intervention in enhancing stress management and autonomic regulation under high-pressure conditions, emphasizing the potential benefits of targeted interventions to improve stress resilience and overall performance in demanding environments such as military aviation [1, 10, 22–27, 29, 32].

In terms of performance, the Wilcoxon rank test (Wilcoxon W) showcased significant results regarding performance variables (in minutes) after the 12-week period within the Yoga group, particularly for the Touch & Go maneuver ($p=0.016$) with a large effect size (0.9444). This significant difference suggests that the Yoga group took more time to complete the Touch & Go maneuver after the intervention, indicating a more careful and deliberate approach [59, 60]. Furthermore, significant differences were observed between groups for the emergency maneuver ($p=0.039$) with a large effect size (0.8333). This indicates that the Yoga group also took more time to complete the emergency maneuvers compared to the control group. These findings suggest that while yoga may improve stress management and precision, it might also lead to longer completion times for certain tasks, in an accuracy vs speed trade-off [59, 60]. However, in military aviation, training leads to both precision and speed [27, 57, 61]. Pilots that had the yoga intervention incorporated into the military training regimen seemed to have a better perception and utilization of the available time for completing the flight simulator emergency, highlighting the need to balance speed and efficiency in high-pressure scenarios [1–7, 10, 11, 26–28, 30].

It is important to assess the number of mistakes pilots made while following the emergency protocol, as we considered optimum performance as the ability to successfully (without mistakes) complete the emergency protocol response to the alternator failure in the minimum amount of

time possible. Time of completion alone does not provide a complete picture of overall performance. The Wilcoxon rank test (Wilcoxon W) revealed significant results regarding the number of errors, between groups after the 12-week period ($p=0.025$) with a large effect size (0.917). Even if the control group number of errors decreased, the Yoga group's mean number of mistakes reduced more substantially. This indicates an improvement in performance for both groups, with the Yoga group showing a higher reduction in errors. A reduction in errors not only reflects improved pilot performance but also directly correlates with enhanced flight safety outcomes. By minimizing errors during critical maneuvers, such as emergency protocols, the risk of accidents and incidents can be substantially reduced, ultimately promoting safer aviation operations. This aligns with International Civil Aviation Organization Human Performance guidelines, which emphasize that minimizing operational errors is essential for maintaining safety margins in complex flight environments, reinforcing the value of interventions that enhance both cognitive and motor precision [62].

The study's limitations include a relatively small sample size, as it represents the entirety of the Tirocinium Pilots in the Portuguese Air Force, making it impossible to have a larger sample. This may affect the generalization of the findings. The short duration of the intervention may not capture all the long-term effects of yoga on HRV and performance. To enhance the robustness of the results, future studies could extend the intervention period, extend the intervention across multiple years of Tirocinium cohorts, or conduct similar studies in other countries Airforce teams for comparative analysis.

The fact that every pilot exhibited similar initial behaviors during the emergency phase indicates that the protocol used was uniformly stressful for all. This consistent level of stress allowed for the observation of the adaptive capabilities of different individuals based on the observed independent variable, that is, with intervention versus without intervention. The subtle changes observed will be related to the individual characteristics of the subjects, evidencing improvements in autonomic regulation or stress resilience from the yoga intervention. In future studies, sequential testing with low-stress and high-stress emergency protocols could also be implemented to compare the results and reveal the intervention's impact across varying stress intensities.

In addition, an in-depth analysis of the recovery phase following the emergency scenario could assess how quickly and effectively participants return to baseline autonomic functioning, uncovering differences that peak stress moments might obscure.

Conclusions

The results of this research demonstrated improved parasympathetic activity and autonomic balance, decreased sympathetic nervous system activity, and lower stress levels regarding the Airforce pilots that participated in the 12-week yoga program [32, 40, 41]. A decrease in HRV is associated with impaired physiological recovery and greater susceptibility to stress-related performance issues, particularly in high-stakes environments such as military aviation [1, 2, 8, 26]. These findings underscore the promising role of interventions aimed at enhancing autonomic flexibility, such as this tailored yoga program.

Regarding performance, the Yoga group pilots were slower within their group during the Touch & Go maneuver and slower when compared to the control group solving the emergency maneuver. Our findings suggest that yoga enhances stress management and precision in high-pressure scenarios, contributing to a significant reduction in errors. However, the increased completion times highlight the need to balance the benefits of improved precision with the necessity of maintaining time efficiency. Integrating yoga into pilot training could be a valuable strategy for enhancing operational performance, particularly in complex and demanding scenarios, by improving pilots' ability to manage stress and maintain optimal compliance by following protocol and reducing mistakes. It should, however, be carefully managed to ensure that the improvements in stress resilience and precision do not come at the expense of operational speed.

Further research into the long-term effects and optimal integration strategies of specific tailored training programs in military aviation pilot training is warranted to fully realize its potential benefits for both pilot individual stress management, military operational performance, and flight safety.

Similar programs can be explored in research applied in populations that deal with high-stress scenarios, involving the control of devices/equipment/vehicles, such as in motor sports where unpredictability may be even more present and where precise control under pressure is also essential.

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Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval and consent to participate Procedures were approved by the Évora University research ethics committee (approval number: 21050) and participants gave written informed consent according to the Helsinki declaration. The study was registered on 19th April 2023 on ClinicalTrials.gov under the identifier NCT05821270.

Consent for publication All the authors and participants give consent for publication.

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