ARTICLE

DOI 10. 52781/cmm.a156

The high-performance military pilot: changes imposed during the flight

El piloto militar de alto rendimiento: cambios generados durante el vuelo

Abstract: This article aims to present and discuss physical fitness, physiological and psychological changes caused by high-performance pilots. High-performance *flight* provides a series of physiological reactions to pilots, such as changes in the cardiovascular, respiratory, and mechanical systems, given the high accelerations and G-force imposed in their training or operations activities. Physical training can contribute to better adaptation to the physiological changes of high-performance *flight*, providing greater endurance, strength, and control of pilots' actions during their activities. Psychological and physical aspects are also affected in pilots, due to the need for quick and assertive responses in moments of pressure and stress, be it physical or mental. Then, high-performance *flight* causes physical and psychological stress to the pilot, with the G force in the Z axis and high acceleration being the main responsible for physiological and mental variations in these professionals.

Keywords: Pilot, Aircraft, Military Personnel, Monitoring Physiologic, Gravitation.

Resumen: Este artículo tiene como objetivo exponer y discutir la condición física y los cambios fisiológicos y psicológicos que generan a los pilotos de alto rendimiento. El vuelo de alto rendimiento provoca una serie de reacciones fisiológicas, como cambios en los sistemas cardiovascular, respiratorio y mecánico, dadas las elevadas aceleraciones y la fuerza G impuesta en las actividades de entrenamiento u operaciones. El entrenamiento físico puede contribuir a una mejor adaptación a los cambios fisiológicos del vuelo de alto rendimiento al atribuir mayor resistencia, fuerza y control de las acciones de los pilotos durante sus actividades. Los aspectos psicológicos y físicos también se ven afectados en los pilotos ante la necesidad de respuestas rápidas y asertivas en momentos de presión y estrés, ya sea físico o mental. Por lo tanto, el vuelo de alto rendimiento provoca estrés físico y psicológico al piloto, en el cual la fuerza G sobre el eje Z y la alta aceleración son las principales responsables de las variaciones fisiológicas y mentales en estos profesionales.

Palabras clave: Piloto, Aeronaves, Militares, Monitoreo, Fisiológico, Gravitación.

Amanda Bárbara da Silva Guimarães
Universidade Estadual do Maranhão.
Licenciatura em Educação Física.
São João dos Patos, Maranhão, Brasil.
amandabarbarasjp@gmail.com

Marcos Alexandre Carvalho Torres
Universidade Estadual do Maranhão.
Licenciatura em Educação Física.
São João dos Patos, Maranhão, Brasil.
marcosalecarvalhot05@gmail.com

Pedro Gabriel Dias Coêlho
Universidade Estadual do Maranhão.
Licenciatura em Educação Física.
São João dos Patos, Maranhão, Brasil.
pedrogabrieldiascoelho@gmail.com

Ana Maria Siqueira Neiva
Universidade Estadual do Maranhão.
Licenciatura em Educação Física.
São João dos Patos, Maranhão, Brasil.
ananeiva997@gmail.com

Joyce Freitas Noleto
Universidade Estadual do Maranhão.
Licenciatura em Educação Física.
São João dos Patos, Maranhão, Brasil.
joycefreitasnoleto@gmail.com

Marcos Antonio do Nascimento
Universidade Estadual do Maranhão.
Programa de Pós-Graduação em Educação Física. São Luís, Maranhão, Brasil.
marcosdonascimento@professor.uema.br

Received: Dec. 13, 2024
Accepted: Jan. 27, 2025

COLEÇÃO MEIRA MATTOS
ISSN on-line 2316-4891 / ISSN print 2316-4833
http://ebrevistas.eb.mil.br/index.php/RMM/index

1 INTRODUCTION

The fascination with flight has always been inherent in humanity. The greatest advances in aviation date back to the 20th century, specifically from 1901 to 1914, a period known as the "Pioneer Era" of aviation (Rangel, 2022).

Humankind has always desired to leave its natural environment, where it developed, and to conquer other environments to which it was not adapted, such as the maritime and aerial realms. Over the years, the aerial domain has proven to be one of the most challenging—and the last to be reached—undoubtedly driving humankind to seek increasingly rapid and efficient solutions for its exploration (Sá, 2015).

Today, more than 2.7 billion people use commercial aviation annually worldwide for various purposes, ranging from business to tourism, due to its efficiency, comfort, and infinite capacity to connect cities and countries. In addition to these aspects, flying is one of the safest means of transportation available (Palhares; Espírito Santo, 2001).

Initially, aviation was focused on the transportation sector. However, due to World War I, the airplane was adapted as a weapon of war (Morrow, 1996). During World War II, fighter aircraft were used extensively and effectively as military weapons (Silva Júnior, 2006). Fighter aircraft are employed for combat flights, including airspace surveillance and direct engagement with other aircraft. For these reasons, this type of flight incurs the highest overloads in military aviation in terms of maneuverability and high accelerations achieved (Lopes, 2018).

Aeronautical evolution has advanced from flights of only a few meters to aircraft capable of flying in nearly all weather conditions, both day and night, at speeds exceeding three times the speed of sound, during missions lasting many consecutive hours and performing a variety of tasks with increasing complexity (Candeias, 2007).

During flight, the pilot may experience various physiological changes, including grayed vision, spatial disorientation, and, in extreme cases, loss of consciousness (G-LOC) (Akparibo; Chumbley, 2020). It is also common for operations to occur in chemically and biologically contaminated environments, accompanied by physical stresses such as jet lag, alterations in the circadian cycle, and environmental stresses due to heat or cold (Gindhart Junior, 1999). In addition to the changes caused by the flight itself, such as vibration, pressurization, dysbarism, hypoxia, temperature variations, air quality, and noise (Gul; Salmanoglu, 2012; Sauvet et al., 2009), the pilot's psychological state can also be impacted by the onboard workload, stress, mission complexity, and situational awareness, which may lead to cognitive and psychomotor consequences and interfere with the transmission and assimilation of information, potentially inducing disorientation and illusions caused by excessive or misinterpreted data (Candeias, 2007).

High-performance flight demands elevated levels of dexterity, physical endurance, sound judgment, and the ability to operate all the aircraft's systems swiftly, alongside excellence in both cognitive and physical capacities (Candeias, 2007).

To mitigate these effects and enhance pilot tolerance, several strategies are employed, such as the use of anti-G suits, reclining seats, and the anti-G straining maneuver (AGSM) respiratory technique (Burns et al., 2001; Yun; Oh; Shin, 2019; Pollock et al., 2019).

In view of the rapid technological evolution in aviation, strategies aimed at effectively promoting greater tolerance to G-forces are necessary. Therefore, it is important to redefine and understand the engineering and physiological parameters that modulate and determine tolerance to high accelerations (Bulbulian et al., 1994) Among the intrinsic factors influencing G-tolerance are sex (Convertino et al., 1998), body mass, body composition, age, stature, and hemodynamic variables such as blood pressure (BP) regulation and heart rate (HR) (Ludwig et al., 1987; Hinghofer-Szalkay, 2011).

The structural and performance evolution of aircraft in recent years has reached extremely elevated levels of capability and speed, but this is not the sole concern; in modern warfare, if the systems and weapon platforms are not integrated, such advancements would be entirely futile. While these factors contribute to operational agility, the pilot remains the critical link in this evolution (Candeias, 2007).

The discussion regarding the influence of physical conditioning on G-tolerance remains a subject of ongoing debate, particularly regarding aerobic and anaerobic conditioning, which still present conflicting data (Bulbulian et al., 1994; Newman, White, & Callister, 1999). In this context, this article aims to present and discuss the physiological alterations, the relationship between physical fitness and G-force, and the psychological aspects in high-performance pilots.

2 METHODOLOGY

This work is a narrative review, a qualitative, descriptive study conducted during May 2023, based on a bibliographic survey using the Lilacs and PubMed databases. These databases were chosen because they index manuscripts in the health field across different contexts and are renowned in the scientific community.

For the search, the following Health Sciences Descriptors (DeCS) were employed: "pilot," "aircraft," "physiologic," "gravitation," and "military personnel."

The formulation of the research question was determined using the PICO acronym (Population, Intervention, Comparison, Outcome), in which P = pilots, I = high-performance flight, C = military personnel, and O = the expected impacts on the human body during high-performance flight. Thus, the guiding question generated was: what are the possible impacts of physical fitness, physiological alterations, and psychological aspects of high-performance flight?

3 PHYSIOLOGICAL ALTERATIONS DURING HIGH-PERFORMANCE FLIGHT

An aircraft is considered high-performance if it can sustain a constant +6G, a force applied to the pilot resulting from their weight, which may vary according to the aircraft's acceleration (Candeias, 2007).

Due to the force resulting from high acceleration, the organic structures most adversely affected in pilots are the cardiovascular system, the respiratory system, and mechanical structures, notably the vertebral column (Balldin, 2001). G-force can be applied by gravity or by an acceleration force that alters body position (Sá, 2015).

During flight, distinct forces resulting from high accelerations act along different axes of movement: the X-axis (sagittal, from front to back), the Y-axis (transverse, from right to left), and the Z-axis (longitudinal, head-to-foot) (Sá, 2015). G-force can be positive or negative, depending on the direction of the force.

In this context, the force applied along the Z-axis in the head-to-foot direction stands out. When the G-force along the Z-axis is positive (+Gz), blood is directed toward the feet, which in turn induces an increase in pressure in the lower extremities. Banks et al. (2008) further suggest that blood displacement increases as +Gz intensifies; for this and other reasons, systolic blood pressure (SBP) may reach values close to 300 mmHg in the lower extremities while being very low in the upper body (Balldin, 2001; Eiken et al., 2012). These hemodynamic alterations may contribute to decreased performance during missions if the pilot is not fully prepared to withstand them.

The cardiovascular alterations resulting from exposure to positive G-forces are caused by changes in the hydrostatic gradient in the venous and arterial systems; these changes affect the size of blood vessels, which in turn influences regional blood flow and overall blood volume (Rainford, 2006).

The first evident manifestation of the cardiovascular effects of acceleration exposure is primarily observed in vision, and at sufficiently high acceleration levels, it leads to loss of consciousness (Albuquerque, 2012). This occurs because the reduction in retinal blood flow causes a loss of peripheral vision, termed "tunnel vision," which, when it progresses to "cannon vision," may quickly be followed by a graying of vision, known as gray-out (Oliveira-Silva, 2016). If hypoxia persists, complete blackout ensues, ultimately resulting in total loss of consciousness (G-LOC) (Silva Júnior, 2006). A study by Xin-Sheng et al. (2012), conducted with pilots in a human centrifuge, demonstrated that crew members under high G-load may experience 12 seconds of complete incapacity due to G-LOC and 16 seconds of relative incapacity.

Exposure to +Gz acceleration produces significant immediate alterations in the distribution of pressure within the arterial and venous systems, inducing changes in blood flow that result in reflex responses involving arterial baroreceptors and, possibly, cardiopulmonary low-pressure receptors and arterial chemoreceptors. Local reflexes also tend to influence the blood pressure response during acceleration exposure (Rainford, 2006, p. 144).

At the onset of exposure to +Gz, blood pressure is maintained but gradually declines with continued exposure of 6 to 12 seconds (Sá, 2015). As blood pressure decreases, the Sympathetic Nervous System (SNS) increases heart rate, enhances contractile force, and accelerates electrical conduction to compensate for these changes (Sá, 2015). Green (2016) emphasizes that the addition of 4.5 +Gz for 30 to 60 seconds can drastically alter blood pressure, reaching up to 300 mmHg in the femoral bed and 0 mmHg in the cerebral arteries.

Due to the redistribution of blood toward the lower extremities, cerebral hypotension may be induced, thereby compromising cerebral perfusion and increasing the risk that the cardiovascular system fails to meet the central nervous system's needs (Rangel, 2022).

Another relevant factor related to pilot health was demonstrated in a study by the Dutch Air Force, which analyzed the degeneration of the vertebral column in 128 F-16 pilots during continuous operations after 8 years. Based on the results, it was concluded that rapid degeneration of the vertebral column occurs; however, this degeneration did not render the study participants physically incapacitated (RTO, 1999). Such a situation may lead to an early reduction in the pilot's professional lifespan.

Other effects caused by acceleration include cardiac arrhythmias, ruptures of skin capillaries, and increased levels of hormones such as adrenaline, noradrenaline, and serum cortisol (Rainford, 2006).

When relating the pilot to the aircraft, the areas most directly or indirectly affected—which can lead to a greater number of potential accident causes—are, in the psychological domain: stress, mission complexity, situational awareness, and onboard workload; in the physical domain: fatigue, decompression sickness, spatial disorientation, and G-force protection; and in the training and selection domain: training programs and the selection process (Candeias, 2007).

4 PHYSICAL FITNESS AND G-FORCE TOLERANCE

The human organism is highly adaptable (Aboitiz & Montiel, 2012; Hofman, 2014); thanks to this capacity, humans can live in diverse environments, which allows the human species to grow and develop across all regions of the planet (Slessarev et al., 2010).

This adaptive capacity does not manifest uniformly in all individuals, as it depends on factors related to the volume and intensity of stimuli (Yashin et al., 2007), responsiveness, and the potential for decline with advancing age (Arbeev et al., 2011). These factors are fundamental for entering and sustaining a high-performance pilot's professional career.

It is important to note that flying is not among the inherent physical abilities of the human species (Boullosa et al., 2013) and, therefore, may lead to undesirable or uncertain adaptations, as humans are not naturally equipped for it.

Flight in high-gravity environments imposes significant metabolic and cardiorespiratory strain on the pilot (Tesch, Hjort, & Balldin, 1983). To reduce the effects resulting from G-force exposure, the military adopts various strategies, including the use of anti-G suits, reclining seats, and the AGSM respiratory technique (Burns et al., 2001; Yun, Oh, & Shin, 2019), with the aim of preventing G-LOC and enhancing cardiovascular adaptation or compensation via repeated exposures to high-load environments (Lin, Wang, & Li, 2012), being maneuvers that ultimately lead to local fatigue and exhaustion in the pilot(Tesch; Balldin, 1984). Another important aspect is that high accelerations diminish the capacity to perform psychomotor tasks; above 7 G, there is a decline in psychomotor ability (Candeias, 2007).

Flight maneuvers can impose considerable physical demands, such as near-maximal heart rate and oxygen consumption exceeding 70% of VO_2max, demands that are sufficient to induce peripheral fatigue resulting from excessive muscular work (Guézennec et al., 2001). Considering the above, it is understood that developing an elevated level of physical activity is necessary (Banks et al., 2008), with an emphasis on increasing aerobic capacity and strength (Newman; White; Callister, 1999).

An improvement in physical fitness is associated with enhanced longevity and better performance in daily activities. According to Palma and Paulich (1999), pilots who are more physically conditioned can more effectively withstand the inherent strains of the profession. Kube (2010) states that maintaining excellent physical condition can minimize the effects of fatigue, and to meet the needs of this very specific population, it is necessary to prescribe training that balances both aerobic and anaerobic exercise. Thus, more specific and personalized training leads to better outcomes for pilots in both training and real missions.

In the military, physical exercise plays a crucial role in the preparation of pilots (Lima et al., 2011; Assa et al., 2011), particularly given the respiratory, cardiovascular, mechanical, psychological, and thermal demands to which aviators are exposed in their duties. Several studies have investigated the influence of physical activity and cardiorespiratory fitness on cardiovascular autonomic regulation (Goldsmith et al., 1992), though the findings are divergent.

With the development of high-performance fighter aircraft that achieve significant G-forces, the demands placed on pilots have increased accordingly. Consequently, the role of physical fitness has received greater attention, and it is likely that the limiting factor for sustaining high +G loads is the low localized muscular endurance in the lower limbs, abdomen, lumbar, and cervical regions (Guimarães, 2017).

Individuals subjected to +G require a cardiovascular apparatus capable of rapidly countering the tendency for blood to pool in the lower extremities; however, aerobic training often imposes, sometimes significantly, a reduced cardiovascular response (Guimarães, 2017).

It is well established that aerobic physical training can induce structural modifications in the cardiovascular system, including increased total blood volume, enlarged cardiac chambers, a reduced baroreflex response in the carotid and aorta, and ventricular hypertrophy (Raven & Pawelczyk, 1993; Martinelli, 1997). These modifications result in an attenuated heart rate and vasoconstriction in response to orthostatic hypotension, which may contribute to orthostatic intolerance due to decreased cerebral vascular volume in the upright position, although these changes are beneficial for exercise.

Aerobic training does not appear to interfere with G-force tolerance (Crisman & Burton, 1988). There is evidence that excessive aerobic fitness may even have negative impacts on gravity tolerance, as it induces an imbalance between parasympathetic and sympathetic activity and increased vagal activation. Guimarães (2017) notes that alterations leading to increased parasympathetic tone result in a diminished cardiac tissue response, causing a longer delay in the increase of heart rate and blood pressure, and ultimately, a deterioration in cerebral blood perfusion.

However, anaerobic training should not be excluded from a training program, as it not only contributes to the development and maintenance of a healthy cardiovascular system and an ideal body composition (Guimarães, 2017) but also reduces the recovery time of muscles used in AGSM maneuvers (Balldin, 1984). This is due to improved blood flow and overall physiological conditions, such as an enhanced blood buffering system, decreased circulating acidity, reduced muscle pain and fatigue, and faster recovery after physical exertion (Palma; Paulich, 1999).

In the context of the physiological needs of fighter pilots, there is significant research interest in analyzing the acute and chronic effects of aerobic and anaerobic training on G-force tolerance. Some studies have demonstrated that strength training increases the ability of individuals to execute the AGSM more effectively, enabling them to withstand higher G-forces for longer periods (Crisman, Burton, 1988; Macdougall et al., 1992; Bain et al., 1997). Furthermore, authors such as Burton, Whinnery, and Forster (1987) have concluded that air combat is predominantly an anaerobic activity.

Anaerobic training produces several physiological modifications, including increased sympathetic activity; hypertrophy of fast-twitch muscle fibers, which more readily enhance their strength and cross-sectional area; reduced muscle capillary density; and an increased ability to tolerate exercise loads (Tesch; Balldin, 1984).

In the study by Bateman et al. (2006), the authors questioned whether an extended period of strength training might fail to increase peripheral vascular beds, thereby promoting greater flow dispersion and, consequently, hypotension that would impair G-force tolerance. However, Epperson, Burton, and Bernauer et al. (1985) observed the effects of resistance training in seven aviators over 12 weeks, during which subjects were exposed to G-loads in a centrifuge ranging from 4.5G to 7G. The results indicated a strong correlation between increased strength in the abdominal and biceps muscles and enhanced G-force tolerance, with biceps strength being particularly critical for withstanding high acceleration loads.

In the military, the literature emphasizes the key role of physical exercise in pilot preparation (Bateman; Jacobs; Buick, 2006; Lima et al., 2011; Assa et al., 2011), especially given the cardiovascular, respiratory, mechanical, psychological, and thermal demands faced by aviators at work. However, there is no consensus regarding the ideal exercise program, as some authors advocate for an emphasis on aerobic training (Palma; Paulich, 1999; Ribas, 2003; Kube, 2010), while others (Caiozzo et al., 2009; Newman; White; Callister, 1999) highlight the importance of anaerobic exercise, leaving a gap in the literature on the effects of combined training.

The study by Ang, Linder, and Harms-Ringdahl (2005) analyzed neck muscle fatigue in fighter and helicopter pilots, linking pain to negative impacts on their performance. The authors emphasized that fighter pilots should reinforce physical training for the neck region, as weakness in this area is more strongly associated with injuries due to muscle fatigue, and consequently, pain may contribute to reduced mission effectiveness. In air-to-air combat, limited neck mobility restricts both external and internal vision, an essential factor for mission success. Neck fatigue and pain also generate discomfort and reduce concentration.

It cannot be ignored that the physical effort and stress experienced by, for example, aviator cadets require more thorough analysis to potentially plan and implement a specialized physical fitness management program for aviators, thereby establishing a benchmark of excellence for the demands of aviation activities (Kube, 2010).

5 PSYCHOLOGICAL ASPECTS OF FLIGHT

The psychological aspects are circumstantially linked to military conduct. It is essential to provide training that prepares the pilot for extreme and adverse situations. Despite such training, psychological consequences may arise. The onboard workload, situational awareness, mission complexity, and stress exacerbate these consequences (Candeias, 2007). These aggravations can interfere with the pilot's performance and may even lead to absences from duty.

The work model of airline pilots is characterized by several factors that can impact the mental health of these professionals. For example, rotating and extended shifts often occur under very unfavorable environmental conditions, such as low humidity, confined workspaces, high noise levels, and poor lighting. In addition to these adverse work conditions, these professionals face additional factors associated with extra workloads, such as intensive training, regular flight simulations, and actual flight tests. Thus, the numerous intrinsic factors in the aviation sector and commercial operations depend on the good physical and psychological health of the pilots (Jackson & Earl, 2006).

There is evidence that high accelerations contribute to a reduction in psychomotor and cognitive capacities. Since high-performance aircraft can produce such accelerations and possess high operational agility, there is a greater likelihood that the pilot's performance will be compromised, thereby reducing their capacities. When imagining oneself in a complex theater of war, commanding an aircraft that can receive a vast amount of information and rapidly change missions, it becomes crucial to limit these sensations. In this context, the workload inside the cockpit is immense, and the pilot must accurately evaluate all information to make effective decisions (Candeias, 2007).

Stress can inhibit the pilot's ability to process information; that is, the higher the level of information received, the greater the difficulty and stress, ultimately preventing the pilot from applying all their knowledge. Stress may provoke various psychological reactions such as excessive stress, tunnel vision, an overwhelming urge to act at any cost, mental regression, and sometimes even complete mental block, all of which can result from operating high-performance aircraft in real situations (Feijo; Câmara; Luiz, 2014) These reactions can be a key determinant between life and death for a pilot in life scenarios.

In view of this, aircraft pilots are a group of professionals who work under a significant level of stress, as highlighted by Feijo, Câmara, and Luiz (2014). Stressors inherent to flying (risk of accidents, turbulence, and adverse weather conditions) and work schedules (irregular cycles of activity and rest, prolonged separation from family, and heavy workloads) require the professional to maintain strict control over processes at various operational levels and interrelated tasks.

In Brazil, the Brazilian Air Force (FAB) began providing psychological support at the Aeronautics Psychology Institute (IPA) in 1988, and in 2013 the Brazilian Association of Aviation Psychology (Abrapav) was established. Both institutions focus on operational safety and promote studies and research on the human psychological factor (Medeiros, 2021).

To achieve standardized and safe operations, an elevated level of dedication, responsibility, and personal health commitment is required of high-performance aircraft pilots. However, maintaining balanced mental and physical health is challenging given the interferences inherent to the profession.

Coelho (2016, p. 10, our translation) notes that "the link between work and psychic illness is increasingly evident due to the high number of cases of depression and suicide in the aviation field."

The pilot's activity requires managing complex systems involving multiple tasks and operational levels. This generates stressors that can impact the professional's performance, which may be related both to work schedules and to flight operations (Feijo; Câmara; Luiz, 2014).

This study has some limitations. Most of the studies discussed focus on short-term exposure to G-forces, while the recovery and long-term effects of repeated exposures are not yet fully understood in the literature. Moreover, the discussions presented here are not generalizable to other types of pilots or individuals with different physical conditioning. Future research should include longitudinal studies to more effectively assess the chronic effects of G-force exposure, more diverse participants, realistic environments, and the application of new real-time monitoring technologies.

Thus, psychological monitoring and evaluation of high-performance pilots is necessary for maintaining both the pilot's health and the effectiveness of missions in training or aerial combat.

6 CONCLUSION

Military activity itself imposes various physiological modifications and adaptations over the course of a career, which are necessary for the successful execution of the training or mission assigned to military personnel. High-performance aviation, with its intense accelerations and G-forces, especially along the Z-axis, places an extremely high physiological load on pilots, which in turn can be minimized via aerobic and anaerobic cardiorespiratory training combined with strength training.

Physical fitness is crucial in preparing high-performance pilots due to the extreme demands imposed by gravitational forces. A balanced approach to aerobic and anaerobic training is essential, as both contribute to meeting the mechanical, physiological, and psychological demands of the profession; consequently, personalized, evidence-based physical training programs must be developed to ensure the safety, performance, and longevity of pilots.

Psychological and mental control is another critical determinant in the military profession, which can be adversely impacted by heavy workloads and/or intensive training, prolonged separation from family, mission complexity, among other factors. This control is indispensable for high-performance pilots given the substantial demands of their tasks and the need for rapid, effective decision-making.

An understanding of the physiological, physical, and psychological effects by both pilots and instructors enables the development of targeted strategies and training aimed at increasing tolerance to G-forces and reducing the risks of loss of consciousness (G-LOC) or disorientation, thereby facilitating safer operations.

Therefore, field studies employing strategies to mitigate the impacts of high-performance flight on pilots are necessary to promote greater pilot longevity and mission effectiveness.

AUTHORS' CONTRIBUTION

All authors contributed equally to the development of the article.

REFERENCES

ABOITIZ, F.; MONTIEL J. F. From tetra pods to primates: conserved developmental mechanisms in diverging ecological adaptations. **Progress in Brain Research**, [*s. l.*], v. 195, p.3-24, 2012. DOI: 10.1016/B978-0-444-53860-4.00001-5

AKPARIBO, I. Y.; CHUMBLEY, E. Aerospace, Gravitational Effects, High Performance *In*: AKPARIBO, I. Y.; CHUMBLEY, E. **StatPearls**. Treasure Island: StatPearls, 2020

ALAGHA, B. *et al*. Hypoxia symptoms during altitude training in professional Iranian fighter pilots. **Air Medical Journal**, [*s. l.*], v. 31, n. 1, p. 28-32, 2012.

ALBUQUERQUE, M. P. **Desenvolvimento de uma centrífuga humana movida a exercício para treinamento de pilotos e pesquisas aeroespaciais**. 2012. 140 f. Dissertação (Mestrado em Engenharia Elétrica) - Pontifícia Universidade Católica do Rio Grande do Sul, Porto Alegre, 2012.

ANG, B.; LINDER, J.; HARMS-RINGDAHL, K. Neck strength and myoelectric fatigue in fighter and helicopter pilots with a history of neck pain. **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 76, n. 4, p. 375-80, 2005. Disponível em: https://pubmed.ncbi.nlm.nih.gov/15828638/. Acesso em: 23 maio 2023.

ARBEEV, K. G. et al. Age trajectories of physiological indices in relation to healthy life course. **Mechanisms of Ageing Development**, [*s. l.*], v. 132, n. 3, p. 93-102, 2011. DOI: 10.1016/j.mad.2011.01.001

ASSA, A. et al. Echocardiographic evaluation and follow-up of cardiac and aortic indexes in aviators exposed to acceleration forces. **Journal of the American Society of Echocardiography**, [*s. l.*], v. 24, n. 10, p. 1163-1167, 2011. DOI: https://doi.org/10.1016/j.echo.2011.06.001

BAIN, B.; JACOBS, I.; BUICK, F. Respiratory muscle fatigue during simulated air combat maneuvering (SACM). **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 68, n. 2, p. 118-125, 1997. Disponível em: https://pubmed.ncbi.nlm.nih.gov/9125087/. Acesso em: 23 maio 2023.

BALLDIN, U. I. Acceleration effects on fighter pilots acceleration-induced loss of consciousness medications for pilots of high-performance aircraft. In: BALLDIN, U. I *et al*. **Aceleration effects on fighter pilots**. Medical Aspects of Harsh Environments. [*S. l.*]: [*s. n.*], 2001.

BALLDIN, U. I. Physical training and +Gz tolerance. **Aviation, Space, and Environmental Medicine**, [*s. l.*], p. 991-992, 1984.

BANKS, R. D. et al. Human Response to Acceleration. *In*: DAVIS, J. R. **Fundamentals of aerospace medicine**. 4. ed. Philadelphia: [*s. n.*], 2008.

BATEMAN, W. A.; JACOBS, I.; BUICK, F. Physical conditioning to enhance +Gz tolerance: issues and current understanding. **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 77, n. 6, p. 573-580, 2006. Disponível em: https://pubmed.ncbi.nlm.nih.gov/16780233/. Acesso em: 5 jun. 2023.

BOULLOSA, D. A. et al. Do Olympic Athletes Train as in the Paleolithic Era? **Sports Medicine**, [*s. l.*], v. 43, n. 10, p. 909-17, 2013. DOI: 10.1007/s40279-013-0086-1.

BULBULIAN, R. et al. The effects of strength training and centrifuge exposure on +Gz tolerance. **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 65, n. 12, p. 1097-1104, 1994. Disponível em: https://pubmed.ncbi.nlm.nih.gov/7872910/. Acesso em: 5 jun. 2023.

BURNS, J. W. et al. Protection to+ 12 Gz. **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 72, n. 5, p. 413-421, 2001.

BURTON, R. R.; WHINNERY, J. E.; FORSTER, E. M. Anaerobic energetics of the simulated aerial combat maneuver (SACM). **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 58, n. 8, p. 761-767, 1987. Disponível em: https://pubmed.ncbi.nlm.nih.gov/3632535/. Acesso em: 5 jun. 2023.

CAIOZZO, V. J. et al. Artificial gravity as a countermeasure to microgravity: a pilot study examining the effects on knee extensor and plantar flexor muscle groups. **Journal of Applied Physiology**, [*s. l.*], v. 107, n. 1, p. 39-46, 2009. DOI: 10.1152/japplphysiol.91130.2008

CANDEIAS, C. J. G. **Impacto Provocado pelo Voo em Aviões de Alta Performance no Organismo Humano**. 2007. 46 f. Trabalho (Investigação Individual) - Instituto de Estudos Superiores Militares, Curso de Promoção a Oficial Superior da Força Aérea, Lisboa, Portugal, 2007. Disponível em: http://hdl.handle.net/10400.26/12660. Acesso em: 5 jun. 2023.

COELHO, D. R. **Transtornos Mentais em Aeronautas Brasileiros e a Segurança Operacional**. 2016. 63 f. TCC (Graduação) - Curso de Ciências Aeronáuticas, Universidade do Sul de Santa Catarina, Palhoça, 2016. Disponível em: https://repositorio.animaeducacao.com.br/bitstream/ANIMA/8112/1/Monografia%20-DANIELA%20RAMOS%20COELHO.pdf. Acesso em: 26 ago. 2023.

CONVERTINO, V. A. High sustained +Gz acceleration: physiological adaptation to high-G tolerance. **Journal of Gravitational Physiology**, [*s. l.*], v. 5, n. 1, p. 51-54, 1998. Disponível em: https://pubmed.ncbi.nlm.nih.gov/11542364/. Acesso em: 26 ago. 2023.

CRISMAN, R. P.; BURTON, R. R. **Physical fitness program to enhance aircrew G tolerance**. [*S. l.*]: Naval Aerospace Medical Research Laboratory, 1988.

EIKEN, O. et al. G tolerance vis-à-vis pressure-distension and pressure-flow relationships of leg arteries. **Europena Journla Applied Physiology**, [*s. l.*], v. 112, n. 10, p. 3619-3627, 2012. DOI: 10.1007/s00421-012-2349-1

EPPERSON, W.; BURTON, R. R.; BERNAUER, E. M. Effectiveness of specific wright training regimens on simulated aerial combat maneuvering g tolerance. **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 56, n. 5, p. 534-539, 1985. Disponível em: https://pubmed.ncbi.nlm.nih.gov/4015564/. Acesso em: 26 ago. 2023.

FEIJO, D.; CAMARA, V. M.; LUIZ, R. R. Aspectos psicossociais do trabalho e transtornos mentais comuns em pilotos civis. **Caderno de Saúde Pública**, Rio de Janeiro, v. 30, n. 11, p. 2433-2442, 2014. DOI: https://doi.org/10.1590/0102-311X00151212

GINDHART JR, R. T. **The air force physical fitness program is it adequate?** Air Command and Staff College. [*S. l.*]: Air University. USAF.1999.

GOLDSMITH, R. L. et al. Comparison of 24-hour parasympathetic activity in endurance-trained and untrained young men. Journal of the American College of Cardiology, [*s. l.*], v. 20, n. 3, p. 552-558, 1992. DOI: 10.1016/0735-1097(92)90007-a

GREEN, N. D. C. Long duration acceleration. *In*: GREEN, Nicholas. **Ernsting's aviation and sapace medicine**. 5. ed. Boca Raton: CRC Press, 2016. p. 131-156.

GUIMARÃES, A. O. B. A influência do treinamento aeróbio e anaeróbio na performance do piloto de caça. **Revista de Educação Física**, [*s. l.*], v. 75, n. 133, 2017. Disponível em: https://revistadeeducacaofisica.emnuvens.com.br/revista/article/view/372. Acesso em: 10 jan. 2023.

GUL, M.; SALMANOGLU, M. Long-term high +Gz effects on cardiac functions in the pilots. **Anadolu Kardiyol Derg**, [*s. l.*], v. 12, n. 8, p. 675, 2012. DOI: 10.5152/akd.2012.245

HINGHOFER-SZALKAY H. Gravity, the hydrostatic indifference concept and the cardiovascular system. **European Journal Applied Physiology**, [*s. l.*], v. 111, n. 2, p. 163-174, 2011. DOI: 10.1007/s00421-010-1646-9

HOFMAN, M. A. Evolution of the human brain: when bigger is better. **Front Neuroanat**, [*s. l.*], v. 27, p. 8-15, 2014. DOI: 10.3389/fnana.2014.00015

JACKSON, E. M.; DISHMAN, R. K. Cardiorespiratory fitness and laboratory stress: A meta-regression analysis. **Psychophysiology**, [*s. l.*], v. 43, n. 1, p. 57-72, 2006. DOI: 10.1111/j.1469-8986.2006.00373.x.

KUBE, L. C. Adaptações fisiológicas do organismo ao exercício físico capacitação física e aptidão físico-profissional do aviador. *In*: SEMINÁRIO DE ESTUDOS: PODER AEROESPACIAL E ESTUDOS ESTRATÉGICOS, II., Rio de Janeiro. **Anais** [...]. Rio de Janeiro, 2010.

LIMA, A. H. R. A. et al. Efeito agudo da intensidade do exercício de força na modulação autonômica cardíaca pós-exercício. **Arquivos Brasileiros de Cardiologia**, Rio de Janeiro, v. 96, n. 6, p. 498-503, 2011. DOI: https://doi.org/10.1590/S0066-782X2011005000043

LIN, P. C.; WANG, J.; LI, S. C. Subjective stress factors in centrifuge training for military aircrews. **Applied Ergonomics**, [*s. l.*], v. 43, n. 4, p. 658-663, 2012. DOI: 10.1016/j.apergo.2011.10.002

LOPES, J. S. C. O Acordo de Compensação Offset entre Brasil e Suécia: o Projeto F-x2 e o Gripen Ng. **Revista Perspectiva**, [*s. l.*], v. 11, n. 21, 2018. Disponível em: file:///C:/Users/marco/Downloads/adanilevicz,+3+Grippen+ng.pdf. Acesso em: 25 fev. 2023.

LUDWIG, D. A. et al. Logistic risk model for the unique effects of inherent aerobic capacity on +Gz tolerance before and after simulated weightlessness. **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 58, n. 11, p. 1057-1061, 1987. Disponível em: https://pubmed.ncbi.nlm.nih.gov/3689269/. Acesso em: 25 fev. 2023.

MACDOUGALL, J. D. et al. Factors affecting blood pressure during heavy weight lifting and static contractions. **Journal Applied Physiology (1985)**, [*s. l.*], v. 73, n. 4, p. 1590-1597, 1992. DOI: 10.1152/jappl.1992.73.4.1590

MEDEIROS, P. T. A. **Contribuições da Psicologia Para a Saúde Mental do Aeronauta**. 2021. 27 f. TCC (Graduação) - Curso de Ciências Aeronáuticas, Pontifícia Universidade Católica de Goiás, Goiânia, 2021. Disponível em: https://repositorio.pucgoias.edu.br/jspui/handle/123456789/1719. Acesso em: 16 out. 2022.

MORROW, J. R. Expectation and Reality: The Great War in the Air*. **Airpower Journal**, [*s. l.*], 1996. Disponível em: http:// www.airpower.Maxwell.af.mil/airchronicles/apj/apj96/win96/morrow.pdf. Acesso em: 25 fev. 2023.

NEWMAN, D. G.; WHITE, S. W.; CALLISTER, R. Patterns of physical conditioning in Royal Australian Air Force F/A18 pilots and the implications for 1 Gz tolerance. **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 70, n. 8, p. 739-744, 1999. Disponível em: https://pubmed.ncbi.nlm.nih.gov/10447045/. Acesso em: 26 ago. 2023.

OLIVEIRA-SILVA, I. **Respostas autonômicas e cardiovasculares em voo e sua relação com a aptidão física**. 2016. 155 f. Tese (Doutorado em Educação Física) - Universidade Católica de Brasília, Brasília, DF, 2016.

PALHARES, G. L.; ESPÍRITO SANTO, R. A. JR. O Turismo é o Transporte Aéreo como Multiplicadores Socioeconômicos. *In*: SETTI, J. R. A.; LIMA JR., L. F. (eds.). Panorama Nacional da Pesquisa em Transportes 2001. *In*: CONGRESSO DA ASSOCIAÇÃO NACIONAL DE PESQUISA E ENSINO EM TRANSPORTES (ANPET), XV., 2001, Campinas. **Anais** [...]. Campinas, 2001. p. 225-232.

PALMA, A.; PAULICH, C., **A influência da aptidão física aeróbia sobre o desgaste em voo dos pilotos de caça**. [*S. l.*]: ENEGEP, 1999.

POLLOCK, R. D, et al. Hemodynamic Responses and G Protection Afforded by Three Different Anti-G Systems. **Aerospace Medicine and Human Performance**, [*s. l.*], v. 90, n. 11, p. 925-933, 2019. DOI: 10.3357/amhp.4927.2019

RAINFORD, J. D.; GRADWELL, P. D., **Ernsting's Aviation Medicine**. 4. ed. London: Hodder Arnold, 2006. 864 p.

RANGEL, M. V. S. **Modulação autonômica em pilotos militares de combate e transporte da Força Aérea Brasileira: um estudo caso-controle**. 2022. 63 f. Dissertação (Mestrado em Ciências do Exercício e do Esporte) – Instituto de Educação Física e Desportos, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 2022.

RAVEN, P. B.; PAWELCZYK, J. A. Chronic endurance exercise training: a condition of inadequate blood pressure regulation and reduced tolerance to LBNP. **Medicine Science Sports Exercise**, [*s. l.*], v. 25, n. 6, p. 713-721, 1993. Disponível em: https://pubmed.ncbi.nlm.nih.gov/8321109/. Acesso em: 5 jun. 2023.

RIBAS, P. R. **O fenômeno da fadiga central na pilotagem de helicópteros: o efeito da condição física aeróbia sobre o comportamento psicofisiológico**. 2003. 129 f. Dissertação (Mestrado em Educação Física). Universidade Gama Filho, Rio de Janeiro, 2003.

NATO RTO-MP-33 AC / 323 (HFM) TP / 13. Operational Issues of Aging Crewmembers. 1999. Disponível na internet em: <http://www.rta.nato.int/panel.asp?panel=HFM&topic=pubs>

SÁ, G. B. **Efeitos fisiológicos da aviação de combate e do condicionamento cardiorrespiratório sobre o controle autonômico cardiovascular**. 2015. 98 f. Dissertação (Mestrado em Ciências Cardiovasculares) – Faculdade de Medicina, Universidade Federal Fluminense, Niterói, 2015.

SAUVET, F. et al. Heart rate variability in novice pilots during and after a multi-leg cross-country flight. **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 80, n. 10, p. 862-869, 2009. DOI: 10.3357/asem.2531.2009

SILVA JÚNIOR, F. C. **Atividade física dos pilotos de caça da FAB: análise da realidade e proposição de estratégias para implantação da programas de treinamento específicos**. Dissertação (Mestrado em Ciências Aeroespaciais) -Universidade da Força Aérea, Rio de Janeiro, 2006.

SILVA, Y. **Alterações tomográficas dos seios paranasais em pilotos de caça por meio de imagens tomográficas**. 2020. 139f. Tese (Doutorado em Ciências) - Universidade de São Paulo, São Paulo, 2020.

SLESSAREV, M. et al. Differences in the control of breathing between Andean highlanders and lowlanders after 10 days acclimatization at 3850 m. **Journal Physiology**, [*s. l.*], v. 588, p. 1607-1621, 2010. DOI: https://doi.org/10.1113/jphysiol.2009.186064

TESCH, P. A.; BALLDIN, U. I. Muscle fiber type composition and G-tolerance. **Aviation, Space, and Environmental Medicine**, v. 55, n. 11, p. 1000–1003, 1 nov. 1984. Disponível em: https://pubmed.ncbi.nlm.nih.gov/6508678/. Acesso em: 05 jun 2023.

TESCH, P. A.; HJORT, H.; BALLDIN, U. I. Effects of strength training on G tolerance. **Aviation, Space, and Environmental Medicine**, [*s. l.*], v. 54, p. 691-695, 1983. Disponível em: https://pubmed.ncbi.nlm.nih.gov/6626076/. Acesso em: 5 jun. 2023.

YASHIN, A. I. et al. Stochastic model for analysis of longitudinal data on aging and mortality. Mathematical Biosciences, [*s. l.*], v. 208, n. 2, p. 538-551, 2007. DOI: https://doi.org/10.1016/j.mbs.2006.11.006

YUN, C.; OH, S.; SHIN Y. H. AGSM Proeficiency and Depression Are Associated With Success of High-G Training in Trainee Pilots. **Aerospacial Medicine and Human Peformance**, [*s. l.*], v. 90, n. 7, p. 613-617, 2019. DOI: 10.3357/amhp.5323.2019

XIN-SHENG, C. et al. Visual Symptoms and G-Induced Loss of Consciousness in 594 Chinese Air Force Aircrew—A Questionnaire Survey. **Military Medicine**, [*s. l.*], v. 177, n. 2, p. 163-168, 2012. DOI: 10.7205/milmed-d-11-00003