ARTICLE

Anti-G Straining Maneuver: a narrative review

Manobra Anti-G: uma revisão narrativa

ABSTRACT

Background: Increasingly valuable, sophisticated, and powerful aircraft are developed and incorporated into the armed forces. Technological advances are notable for increasing physiological load during the flight, making human resources a limiting factor in such operations. It is necessary to understand the physiological demands to which aircraft pilots are exposed, especially combat pilots. **Objective:** This study aimed to present: i. the physiological consequences on the human body due to high accelerative forces during high-performance flights; ii. the efficiency of the Anti-G Straining Maneuver (AGSM) countermeasure to such consequences; and iii. the state of the art about surface electromyography's uses (sEMG) in AGSM. **Method:** It was conducted a bibliographic search in the PubMed database using the keywords "anti-G effort maneuver" and "electromyography" and their synonyms. After this, a narrative review of the results was performed. This research model allows a comprehensive discussion about the topic, enabling an in-depth contextualization in a prosperous field of study. These characteristics are suitable for detecting literature gaps and directing the research discussion. **Discussion:** There is a consensus in the literature that AGSM is the most effective resource to prevent loss of consciousness induced by G-load (G-LOC). The sEMG is an affordable and useful tool for AGSM training, especially given the unavailability of human centrifuges. The current literature on the application of sEMG in the context of AGSM training is limited, presenting a diversity of objectives, methodology, and analyzed parameters. **Conclusion:** The use of sEMG as real-time biofeedback can improve the pilot's muscle control skills during AGSM.

Keywords: Aviation. Acceleration. Electrophysiology. Loss of Consciousness. Electromyography.

RESUMO

Introdução: Aeronaves mais valiosas, sofisticadas e potentes são incorporadas às forças armadas. Os avanços tecnológicos são notáveis por aumentar a carga fisiológica durante o voo, tornando os recursos humanos um fator limitante nessas operações. É necessário entender as demandas fisiológicas às quais os pilotos de aeronaves estão expostos, especialmente os pilotos de combate. **Objetivo:** Este estudo teve como objetivo apresentar: i. consequências fisiológicas no corpo humano devido às altas forças de aceleração durante voos de alto desempenho; ii. eficiência da contramedida AGSM para tais consequências; e iii. estado da arte sobre os usos da eletromiografia de superfície em AGSM. **Método:** Busca bibliográfica na base de dados PubMed usando as palavras-chave "anti-G straining maneuver" e "electromyography" e seus sinônimos foi conduzida, seguida de uma revisão narrativa dos resultados, que permitiu uma discussão abrangente sobre o tema, possibilitando uma contextualização aprofundada em um campo de estudo próspero. Essas características são adequadas para detectar lacunas na literatura e direcionar a discussão da pesquisa. **Discussão:** Há um consenso na literatura de que o AGSM é o recurso mais eficaz para prevenir a perda de consciência induzida por carga G. A sEMG é uma ferramenta acessível e útil para o treinamento de AGSM, especialmente quando indisponível centrífugas humanas. **Conclusão:** A literatura atual sobre a aplicação do sEMG no contexto do treinamento do AGSM é limitada, apresentando uma diversidade de objetivos, metodologia e parâmetros analisados. Contudo, seu uso como biofeedback em tempo real pode melhorar as habilidades de controle muscular do piloto durante o AGSM.

Palavras-chave: Aviação. Aceleração. Eletrofisiologia. Perda de Consciência. Eletromiografia.

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1 Introduction

Avionics development has provided increasingly valuable, sophisticated, and powerful aircraft for various armed forces. In this context, it is prudent for airmen to understand their physiological limitations and adopt actions that allow operational performance and safety (Shaw and Harrell, 2023). Humans are essentially terrestrial, and their bodies may not adapt completely under intense gravitational loads – G-load (Federal Aviation Administration, 2022). One of the most challenging environments for pilots is fighter flights or combat due to the characteristics of these flights: fast maneuvers, tight turns, and sudden changes in direction (Federal Aviation Administration, 2022).

The capacity of the human body's physiological responses is a relevant factor that may limit high-performance aerial activity because probably faster aircraft demand higher pilot physiological adaptations (Federal Aviation Administration, 2022). Consequently, for airmen to withstand such environment they must have access to supplemental oxygen, a pressurized pilot's cabin, anti-G suits during flights, and receive efficient physiological adaptation training periodically (Shaw and Harrell, 2023).

In this scenario, fighter pilots must have flight skills and be able to appropriate physiological adaptations (Federal Aviation Administration, 2022). The lack of technological resources that enable the pilot to adapt to the physiological demands of high-performance piloting or deficient human performance for such aerial activity would decrease rates of aviation incidents and accidents that would promote high economic impacts and others immeasurable as life.

G-load is an extreme physical stress that stimulates several physiological changes that may cause G-LOC, the loss of consciousness during flight induced by G-load (Shaw and Harrell, 2023). There are combat aircraft that can cause high sustained G-loads on the pilot (+9Gz), and under such circumstances, the G-LOC occurrence will depend on the pilot's preparation to withstand the G-load (Choi *et al.*, 2015). Pilots qualified to fly such aircraft must complete a specific training to withstand extreme G-load, which includes learning the Anti-G Straining Maneuver (AGSM) technique, considered the most effective action to prevent G-LOC (Burns *et al.*, 2001; David and David, 2006). AGSM is the association of periodic cycles of abrupt voluntary expirations with isometric muscular contraction of the abdomen, lower back, glute and lower limbs of the body that cause the maintenance of blood flow in the upper part of the body (Burns *et al.*, 2001; David and David, 2006).

Surface electromyography (sEMG) is a technique for evaluating electrophysiological activity that allows instantaneous biofeedback of the muscle activity being evaluated (Chen *et al.*, 2004). Thus, sEMG is an implementable tool to assess the muscular contractions produced by the pilot during AGSM. However, the use of sEMG as biofeedback for AGSM instruction is incipient,

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The objective of this study is to explore the physiological effects of accelerative forces, the efficacy of AGSM in preventing G-LOC, and the advanced application of sEMG for AGSM training. A narrative review was selected as the research methodology to facilitate a comprehensive discussion on the subject, allowing for a deeper contextualization within this dynamic field of study. These characteristics are appropriate for this study, moving towards identifying gaps and directing future research. The method adopted in this narrative review was a bibliographic search in the PubMed database using a Boolean equation that associated the keywords "anti-G straining maneuver" and its synonyms and the descriptor "electromyography" and synonymous terms (DeCS/MeSH). The final equation was: ("Agsm"[tiab] OR "anti G straining maneuver"[tiab]) AND ("Electromyography"[Mesh] OR Electromyograph*[tiab] OR Surface Electromyograph*[tiab]). The references list of all selected and retrieved articles were also reviewed.

2 Literature Review

2.1 Accelerations and Physiology

During the flight, accelerations and maneuvers may stimulate the G-load, causing effects on the body in the vertical (z), anteroposterior (x), and mediolateral (y) axes. Depending on the direction of load relative to the reference point, these loads can be positive or negative (Davis *et al.*, 2012). The greater the intensity of the G-load, the more severe the effects on human physiology, and the most important acceleration item for human physiology during combat flights are vertical accelerations (Gz), that is, accelerative forces in the craniocaudal directions.

In aerial maneuvers that cause +Gz, the pilot's blood is pushed toward the lower limbs and tends to accumulate there, leading to the pilot's stagnant hypoxia. It is a phenomenon induced by reduced venous return, cardiac output, compromised blood and oxygen supply to the individual's eyes and brain (Federal Aviation Administration, 2022).

The forces produced on the pilots progress/regress geometrically, in this way, an individual weighing 70.0 kilograms exposed to a +3Gz load will receive a force equivalent to three times its mass (210.0 kg). Under these conditions, the individual's upper and lower limbs do not move freely, the internal organs move backward and the diaphragm moves downwards, increasing respiratory disorders (Banks *et al.*, 1994). On exposure to +1Gz, the difference between the blood pressures of the brain and heart is ~25 mmHg, while on exposure to +5Gz, this difference becomes ~120 mmHg. In this last condition, the individual's heart must be able to pump arterial blood with a minimum blood pressure of 120mmHg to maintain the oxygen supply to the brain. Therefore, the increase of +1Gz of load on the individual induces a decrease in blood pressure, at the eye level, between 22 and 25 mmHg (Cheana, 2011).

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Before G-LOC, symptoms progress through some stages: tunnel vision, gray-out, black-out, almost loss of consciousness (A-LOC), and G-LOC. Initially, at an exposure of approximately +4Gz, the deficiency of blood perfusion to the retina induces the tunnel vision pilot, that is gradual loss of peripheral vision; followed by gray-out, which refers to the vision becomes grayish; culminating with probable black-out, that is the disappearance of vision. At +5Gz exposure, cerebral circulation is affected and symptoms of A-LOC or G-LOC may affect the pilot. The rate of progression of the Gz load, permanency at the Gz load, and magnitude of the Gz load correspond to the total magnitude of exposure to the G-load, which defines the behavior of the individual's physiological response (Whinnery and Forster, 2013).

G-LOC is the altered perception in the individual due to the absence of reality caused by a sudden and critical reduction in cerebral blood circulation due to increased G force. In G-LOC there is a period of unconsciousness or absolute incapacity followed by a conscious period, but as a relative disability, in which convulsions may occur (David and David, 2006). There is a refractory period of approximately 5 seconds in which G-LOC does not occur (Whinnery and Forster, 2013) however, for practical purposes, the total incapacitation time varies between 20 and 30 seconds (David and David, 2006).

As a counterbalance to resist the effects of Gz load, there are strategies based on the use of accessories such as anti-G suit - inflatable suit that puts pressure on the pilots' lower limbs and waist region according to the G-load information detected by the aircraft; inclined seats - ejection seats ergonomically designed to keep the pilot's torso reclining, reducing the distance between the heart and the head and facilitating pressure equalization between the organs; oxygen mask - masks attached to the helmet that constantly provide oxygen to the pilot. Other strategies are based on human resources development such as specific physical conditioning programs, and body maneuvers training, e.g., AGSM.

2.2 Anti-G Straining Maneuver

AGSM provides pilot endurance capabilities up to +4Gz (David and David, 2006), the most effective strategy to prevent G-LOC (Burns *et al.*, 2001; Yun *et al.*, 2019). It consists of two components performed simultaneously: respiratory and muscular. In the respiratory component, the pilot inhales preparatory to the AGSM and maintains a controlled rhythm with gas exchanges every three seconds during the AGSM. Gas exchange may be performed with gas exhalation against the occluded glottis (L1 maneuver) or partially occluded (M1 maneuver). In the muscular item, the pilot isometrically contracts the lower limb muscles, glutes, and abdomen during an AGSM (Tu *et al.*, 2020).

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Both types of AGSM maneuvers, M1 and L1, promote increased abdominal and intrathoracic pressure due to contraction of the diaphragm and others respiratory muscles. This pressure is transmitted directly to the large blood vessels and the heart, raising blood pressure. Furthermore, the contraction of the diaphragm prevents the distance between the heart and the head from increasing (David and David, 2006). Such maneuvers cause similar effects on ocular blood pressure however pilots use to choose L1 to cause less laryngeal tension (Burton *et al.*, 1974).

According to a review study (Whinnery and Whinnery, 1990), there is a relationship between G-load tolerance and the execution of AGSM. This study compiled 500 episodes of G-LOC and highlighted that individuals who performed AGSM during G-loading resisted higher levels of gravitational stress (Whinnery and Whinnery, 1990). On the other hand, understanding the influencing factors on AGSM performance is controversial. Although studies report that the effectiveness of AGSM is related to the individual's muscular strength (Tesch *et al.*, 1983; Epperson *et al.*, 1985), there is a report that physical fitness, muscle mass, overall strength and endurance, had no influence for experienced pilots who have suffered or no G-LOC (Park *et al.*, 2016). However, tolerance to G-loads seems to be more dependent on AGSM muscular coordination than on muscular hypertrophy (Park *et al.*, 2016).

Considering that the reduction of arterial flow in the brain induces loss of consciousness, heart rate (HR) is another influencing factor to G-load tolerance since, HR influences underlying mechanisms of modulating blood pressure in the body. Firstly, the maintenance of blood pressure and cerebral perfusion is hampered by the distribution of peripheral blood, especially during exposure to flight accelerations. Therefore, vagal tone leads to bradycardia, which increases the risk of the pilot's subsequent loss of consciousness during flight, reducing tolerance to G-load (Crisman and Burton, 1988). Furthermore, excessive respiratory conditioning induces an imbalance between the body's sympathetic and parasympathetic activity, causing greater vagal activation that can impair G-load tolerance (Crisman and Burton, 1988).

However, the relationships between HR and loss of consciousness are divergent. A retrospective study analyzed records from 873 pilots who performed a theoretical instruction session and a centrifuge training session with high G-loads, identified that the group which failed to resist the load of +7.5Gz for 15 seconds presented higher HR before such G-load, and lower HR under +7.5Gz (Tu *et al.*, 2020). On the other hand, higher rest HR and the greater increase in HR just before the beginning of centrifuge training were correlated with a higher probability of failure on that training. I can indicate that anticipatory stress may compromise the G-load tolerance (Habazettl *et al.*, 2016). Therefore, the understanding that lower resting HR promotes risk for G-LOC is controversial (Van Lieshout *et al.*, 1992).

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Tu *et al.*, (2020) observed that the group which did not resist +7.5Gz for 15 seconds had the higher increases in HR after completing exposure to +6Gz for 30 seconds. They also identified that body mass index (BMI), individual baseline and effort of G-load tolerance profile, and an AGSM score were associated with G-load tolerance. The authors suggest that the capacity of the cardiovascular system to relax and recover, baroreflex response, appears more important for G tolerance than basal HR. Furthermore, the authors indicate the importance of characterizing the AGSM by evaluating the performance of its two components during G-load tolerance training (Tu *et al.*, 2020).

Anthropometric, physiological, and flight experience factors also influence G-load tolerance. However, age, height, body mass, blood pressure, cholesterol levels, and flight hours seem to have a weak influence on pilots' G-load tolerance (Webb *et al.*, 1991; Forster *et al.*, 1999). In contrast, anti-G suit use and AGSM performance have strong direct correlations with G-load tolerance (Gillingham and Fosdick, 1988), as mentioned previously.

G-tolerance due to remaining under the G-load is when the pilot fatigues during continuous G-load exposure; whether constant or varied (Park *et al.*, 2015). Thus, fatigue is the main limiting factor for G-tolerance since the pilots exposed to high G-load must continually perform AGSM to avoid an incapacitation. In this sense, the muscular component assessment to characterize AGSM gains more importance. Additionally, muscle activity assessment and muscle fatigue during AGSM can be assessed by using surface electromyography (sEMG).

2.3 Surface Electromyography in AGSM Studies

The sEMG is used for three main objectives: identifying the beginning of muscle activation, measuring the force produced by a muscle, and predicting fatigue processes (De Luca, 1997). This technique allows the evaluation and monitoring of neuromuscular functions with or without biofeedback; the possibility of use for examination and treatment of pathophysiological conditions, ergonomic and occupational disorders, muscular fatigue, musculoskeletal pain, rehabilitation of neuromuscular injuries, control of prostheses; and sports training and performance (Merletti and Farina, 2016).

sEMG is an advantageous technique as it is non-invasive, painless, and does not harm the individual's epidermis. This technique consists of electrodes applied to the epidermis over the assessed muscle in order to acquire the muscular electrical activity (Merletti and Farina, 2016). Due to such characteristics, clinical studies and research widely use sEMG, especially in the human movement area.

The biological signal processing from sEMG allows the estimation of muscle contraction and muscle fatigue parameters, for example: the number of motor units recruited, the types of fibers

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contracted, and the conduction speed of the action potential (Garcia and Vieira, 2011). In the present review, it was observed that the muscle sEMG used on AGSM studies were predominantly: root mean square - RMS; absolute integrated value - IAV; absolute mean value - MAV or ARV; wavelength - WL; and median frequency - MD (Choi *et al.*, 2015; Kim *et al.*, 2017).

To our knowledge, Cornwall and Krock (1992) were the pioneers in the use of sEMG in pilots performing AGSM in a human centrifuge during G-load. The authors analyzed the RMS of the erector spine, external oblique, biceps femoris, vastus lateralis, and gastrocnemius lateralis muscles. They found a reduction in the amplitude of electromyographic muscle activity in lower limbs when the pilots were submitted to intense G-load (decrease of -61.5% RMS); and identified traces of muscle fatigue.

In a study published in 2003 (Oksa *et al.*, 2003) that used the sEMG technique in pilots during AGSM in an environment with 1 G-load, it was found that wearing lumbar support on the seat back increased muscle contraction activity of pilots, mainly for the rectus abdominal and spinal erector muscles. The study suggested that lumbar support positions the riders' torso more upright, which favors the production of muscular force. Furthermore, in the pilots' subjective assessment, lumbar support favored the pilots' AGSM performance (Oksa *et al.*, 2003).

Chen and co-workers (Chen *et al.*, 2004) evaluated the respiratory component of AGSM performed by 20 individuals (8 experienced pilots and 12 inexperienced) under high G-load. The authors found that the pilots' experience influenced the muscular activity of the buccinator muscle during AGSM. The respiratory cycle of experienced pilots (2.2 sec.) was longer than that of inexperienced pilots (1.8 sec.). The muscular activity rate of the pilots' buccinator muscle was higher during G-load but experienced pilots had a higher rate than inexperienced individuals (Chen *et al.*, 2004). Increasing the respiratory cycle time allows the pilot to reduce the number of breaths and, consequently, reduce the vigorous activations of the respiratory muscles during the AGSM over time, inducing the pilot's energy savings. Additionally, the sequence of muscle recruitment patterns in AGSM was different between the groups. The sequence of muscle recruitment by experienced pilots was: the buccinator, rectus abdominal, latissimus dorsi, diaphragm, intercostals, pectoralis major and sternocleidomastoid muscles sequentially, while the inexperienced participants sequentially recruited the buccinator, sternocleidomastoid, pectoralis major, intercostals, latissimus dorsi diaphragm, and rectus abdominal muscles (Chen *et al.*, 2004).

The study results by Chen and co-workers (Chen *et al.*, 2004) indicated that the acquisition of muscular coordination of AGSM execution is influenced by experienced pilots (Chen *et al.*, 2004). This suggests that based on the muscle recruitment pattern of experienced pilots it is possible to provide targeted training of the muscular component - muscle recruitment sequencing, and respiratory

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- breathing cycle time, of AGSM to contribute to the efficiency of AGSM performance. Then, AGSM improvement might take time and the training should be a continuous process during a pilot's career.

The average increase in human centrifuge G-load tolerance after an AGSM training session in 25 untrained Indian Air Force pilots was +0.4Gz (Sah *et al.*, 2018). The authors evaluated the muscular activity of the pilots during the execution of the AGSM using sEMG and they found a greater muscular activity in the lower limbs - vastus lateralis and gastrocnemius, than in the trunk - rectus abdominal and pectoralis. However, did not use the sEMG to monitoring AGSM training sessions, it was used just at centrifuge evaluation (Sah *et al.*, 2018).

The sEMG has been used to investigate the association between muscular contractility and fatigue parameters with AGSM performance. In this context, Choi and collaborators (Choi *et al.*, 2015) proposed an algorithm for processing biological EMG signals that predict G-LOC based on the temporal behavior of the amplitude of gastrocnemius muscle activity during AGSM. The authors identified fatigue of the gastrocnemius muscle in the IAV and WL parameters three seconds before the G-LOC. They suggested this algorithm as biological safety alerts in high-performance flights against G-LOC (Choi *et al.*, 2015). However, the authors did not present reference or fatigue values or thresholds for sEMG.

Studies that use EMGs to evaluate AGSM are methodologically heterogeneous, especially concerning sEMG parameters. Most studies evaluated muscle activity only of the AGSM muscle component, except Chen and co-workers (2004) (Chen *et al.*, 2004) who evaluated both components simultaneously. Furthermore, two studies evaluated AGSM under high Gz loads (Cornwall and Krock, 1992; Sah *et al.*, 2018), demonstrating the few uses of sEMG in AGSM instruction and assessment, and none with biofeedback. However, it is important to validate this methodology in real situations, so that it becomes an evaluable tool for AGSM instruction as an alternative to pilot exposure to G-loads in the human centrifuge.

Biofeedback provides real-time muscular activity to pilots and can be used as an AGSM instruction strategy. The AGSM is a complex motor task in which an isometric contraction of several muscles of the muscular components is associated with intense and cyclical respiratory maneuvers, it is important to ensure that the muscles are recruited appropriately so that the AGSM is efficiently carried out. Therefore, real-time biofeedback can be incredibly useful for AGSM pilots and instructors. Figure 1 contextualizes EMG biofeedback for AGSM from the perspective of the need to develop the human factor in line with technological development.

Figure 1. Diagram of the need for training in AGSM using sEMG as a biofeedback tool, in four stages. 1- Technological advances in fighter aircraft cause an imbalance between the pilot capacity and the aircraft, requiring an increase in the pilot's functional capacity; 2- The machine x human imbalance leads to accidents and an increase in human injuries, causing negative financial and social impacts; 3 – In the situational reality, the continuous training in AGSM to improve

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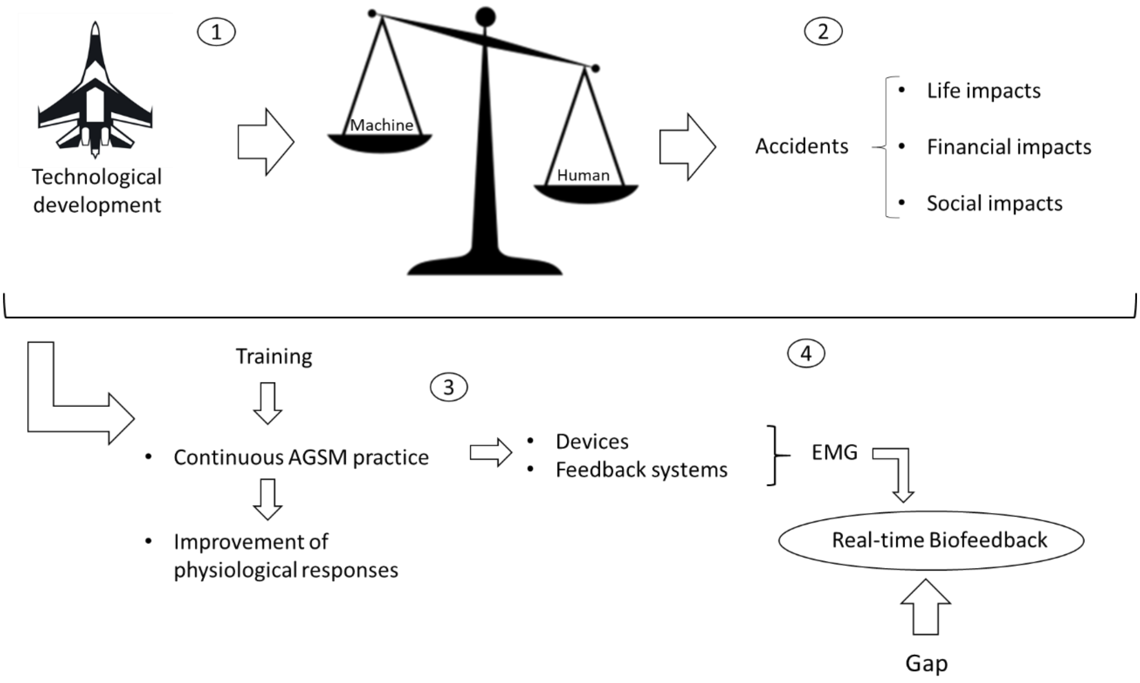
pilots' physiological response capacity is necessary. Equipment such as sEMG and feedback systems are promising for training quality. 4 – sEMG is a system able to evaluate the two components of AGSM (respiratory and muscular) and allows feedback to pilots and instructors about the quality of AGSM. However, sEMG for AGSM training is an incomplete issue, exposing a gap in the literature.



3 Conclusion

The present study aimed to discuss the physiological consequences of acceleration forces, the efficiency of AGSM as a G-LOC prevention action, and the state of the art in the implementation of sEMG for AGSM training. In conclusion, we found that human resources can limit the operational performance of aircraft that apply G loads of +7Gz and that the literature is incipient on the use of sEMG to evaluate AGSM training, with diverse objectives, methodology, and sEMG analysis parameters.

However, AGSM is essential for the pilot to withstand G loads above 7G, indicating the need for continuous operational training of AGSM and sEMG biofeedback as a tool in AGSM training is an open gap in the literature to be explored, especially because it is a useful and economically accessible tool for AGSM training, especially in places that do not have a human centrifuge for AGSM training.

Overall, this study contributes significantly to the evolution of flight safety in air operations and the understanding of human physiology during high-G flights, as it discusses the advantages of AGSM to mitigate G-LOC cases and to perform AGSM training through the use of EMG, especially when there is no human centrifuge.

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