



Research Progress on Surface Electromyography in Monitoring G-Induced Loss of Consciousness

Zhengyi Yang¹, Chuantao Li², Yongjie Yao^{2,*}

¹ School of Health Science and Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

² Naval Military Medical University, Shanghai 200082, China

* Corresponding author: 648319648@qq.com

Abstract: G-induced Loss of Consciousness (G-LOC) caused by high overload is a primary cause of flight accidents. Although existing anti-G measures are effective, the risk has not been entirely eliminated. Traditional monitoring indicators (such as EEG, ECG, and cerebral oxygen saturation) face limitations in actual flight environments, including signal lag, susceptibility to interference, or high equipment costs. Surface electromyography (sEMG), as a non-invasive, highly sensitive, and real-time physiological indicator, provides a new technical pathway for the early warning of G-LOC. Research confirms that during the critical window approximately 3 seconds prior to the occurrence of G-LOC, the electromyographic features (such as RMS and WL) of anti-G muscle groups exhibit significant attenuation, reflecting a loss of neuromuscular control capabilities. Compared to the neck and abdomen, the gastrocnemius muscle of the lower leg has been established as the optimal monitoring site due to signal stability. Based on this regularity, researchers have developed G-LOC electromyographic recognition algorithms and constructed real-time warning and wake-up systems integrating head posture monitoring, verifying their engineering feasibility. This paper aims to systematically review the technical principles, feature evolution laws, algorithm progress, and system applications of sEMG in G-LOC monitoring.

Keywords: G-LOC; electromyographic features; anti-G physiology; G-LOC warning

1. Introduction

G-induced loss of consciousness (G-LOC) is one of the primary causes of human-error flight accidents. When the continuous positive acceleration experienced by a pilot exceeds their physiological tolerance limit, organs in the thoracic and abdominal cavities shift and deform, the hydrostatic pressure difference of the blood column increases, and blood redistributes downward to the lower extremities. This results in reduced arterial blood pressure at the eye level, leading to insufficient cerebral blood supply and acute hypoxia, which triggers transient loss of consciousness, also known as high-G incapacitation[1]. The high incidence of G-LOC accidents severely impacts flight safety, potentially causing significant casualties and economic losses. Despite various existing protective measures—such as anti-G suits, anti-G straining maneuvers (AGSM), positive pressure breathing, and reclined seats—playing an important role in increasing pilots' +Gz endurance, the risk of G-LOC has not been completely eliminated[2]. Questionnaire survey data indicates that the incidence of G-LOC is 14.8% [3] among active pilots in the Royal Air Force and 8.2% among Chinese Air Force pilots[4]. Regardless of location, G-LOC remains prevalent in flight. Therefore, developing high-sensitivity real-time G-LOC monitoring and warning technologies is of great significance for ensuring pilot safety.

Existing G-LOC warning indicators include monitoring and analysis of EEG[5], ECG[6], ear pulse[7], head-eye blood flow[8], and cerebral oxygen saturation[9]. However, these indicators have limitations in practical application. While EEG-based detection techniques directly reflect central nervous system activity, they are susceptible to motion artifacts and electromagnetic interference, and signal decoding has significant latency[10]. ECG signals are heavily influenced by environmental factors and exhibit large individual variability[11]. Monitoring ear pulse and cranial arterial pressure in real flight environments is easily affected by anti-G maneuvers, respiratory rate, and equipment stability[12]. Monitoring head-eye blood flow is difficult while pilots perform anti-load maneuvers; although flexible Doppler ultrasound shows potential for monitoring deep blood flow, it is still in the research phase with no mature systems available for use[13]. Cerebral oxygen saturation responses to +Gz show high individual variability, and the monitoring equipment is expensive, requires high precision, and faces many signal interference factors[14]. In contrast, electromyography (EMG) demonstrates unique potential due to its non-invasiveness, sensitivity, and operational simplicity, making it an emerging direction in G-LOC research.

Electromyography (EMG) signals, as key physiological indicators reflecting neuromuscular activation states, can precisely quantify muscle contraction intensity and fatigue resistance characteristics. There is a significant temporal

correlation between the dynamic evolution of EMG signals and the occurrence of G-LOC. Studies show that within a critical time window of approximately 3 seconds before G-LOC, time-domain features representing muscle contraction force (such as RMS, IAV, MAV) and frequency-domain parameters (such as WL) exhibit significant rapid attenuation[15]. This sudden drop in signal energy essentially reflects a decline in anti-G muscle strength or the loss of central nervous system control over muscles. Therefore, real-time monitoring of the EMG signal evolution of key anti-G muscle groups (such as the gastrocnemius) to capture specific physiological precursors prior to loss of consciousness is highly feasible technically.

In summary, surface electromyography (sEMG), by virtue of its non-invasive portability, high sensitivity, strong real-time performance, and resistance to environmental interference, has become one of the physiological monitoring modalities with the most engineering promise for building pilot G-LOC early warning systems. This paper will systematically review the technical principles of sEMG, signal feature evolution laws under high +Gz environments, optimization strategies for key monitoring muscle groups, and recent progress in warning algorithms. It will also deeply analyze current technical limitations and future development directions, aiming to provide a solid theoretical basis and technical reference for the R&D of next-generation anti-G physiological support equipment and intelligent warning systems.

2. Overview of Surface Electromyography

Surface electromyography is the result of action potential sequences fired by multiple active motor units propagating along muscle fibers, filtered by the volume conductor composed of fat and skin, and spatially and temporally superimposed on the skin surface[16]. sEMG is a non-stationary micro-electric signal that is generated 30 to 150 ms prior to limb movement. Its amplitude ranges from 0.01 to 10 mV, with energy mainly concentrated between 0 and 500 Hz[17]. The analysis and processing methods for sEMG signals are primarily divided into time-domain analysis and frequency-domain analysis. Time-domain analysis represents the sEMG signal as a potential/time curve, calculating metrics such as Average EMG (AEMG), Integrated EMG (iEMG), Root Mean Square (RMS), and Variance/Zero Crossings (VAR). Frequency analysis represents the sEMG signal as a potential/frequency spectrum, calculating metrics such as Peak Frequency, Median Frequency (MF/MDF), and Mean Power Frequency (MPF/MNF). Given the advantages of non-invasiveness, high sensitivity, and real-time capability, combined with increasingly portable acquisition equipment, sEMG technology is not only mature in medical rehabilitation and sports science but also shows broad application prospects in ergonomics and aviation medical monitoring.

3. Application Research of EMG in G-LOC Monitoring

3.1 Early Exploration of EMG for G-LOC Detection

Cornwall and Krock (USA) conducted a classic experiment[18]. They recruited 10 male subjects wearing standard anti-G suits to withstand +6Gz overload in a centrifuge until fatigue or visual loss occurred. The study synchronously recorded sEMG signals from the erector spinae, external abdominal oblique, biceps femoris, vastus lateralis, and the lateral head of the gastrocnemius. The study found that as the Anti-G Straining Maneuver (AGSM) continued, the mean amplitude of sEMG dropped significantly by about 35.40%, with the decline in lower limb muscles (61.45%) being far greater than that of trunk muscles (3.45%). This finding quantitatively confirmed for the first time that lower limb muscles are more prone to neural drive reduction or peripheral fatigue during anti-G maneuvers, and this attenuation of EMG activity is highly consistent with pilots' subjective fatigue and decreased anti-G capacity. It established the biological feasibility of sEMG as a G-LOC warning signal and the importance of monitoring lower limb muscles.

Building on this, Choi et al. collected EMG signals from the trapezius, rectus abdominis, and gastrocnemius of subjects through human centrifuge simulation experiments. Using wet electrodes, a 400 Hz sampling rate, and 10–500 Hz bandpass filtering, they extracted seven features: Root Mean Square (RMS), Integrated Absolute Value (IAV), and Mean Absolute Value (MAV) to assess muscle contraction; and Slope Sign Change (SSC), Waveform Length (WL), Zero Crossing (ZC), and Median Frequency (MF) to characterize muscle contraction and fatigue. Results showed that in the 3 seconds prior to G-LOC (the alarm phase), WL, IAV, RMS, and MAV of the gastrocnemius attenuated significantly ($p < 0.01$). The significance of this key finding is that it quantified the prediction window for G-LOC, proving that using the attenuation of EMG signals to provide early warning of loss of consciousness is technically feasible.

3.2 Optimization of EMG Monitoring Sites

To determine the optimal signal acquisition location for improved monitoring accuracy, researchers compared EMG characteristics across different body parts. Kim et al. [19] conducted a comparative analysis of signal changes in the upper trapezius (neck), rectus abdominis (abdomen), and gastrocnemius (calf) before and after G-LOC. They found that after G-LOC occurred, EMG feature values such as RMS and IAV in neck muscles were actually higher than in the normal state,

likely related to neck stiffness caused by loss of consciousness; thus, the neck is unsuitable as a monitoring point. Conversely, EMG signals in the calf area showed a more significant decline of approximately 17%-18%. Therefore, the gastrocnemius was established as the preferred monitoring site. Li et al. [20] further refined the selection of lower limb monitoring sites by comparing the gastrocnemius and tibialis anterior on the lower leg. They found that although the tibialis anterior could also provide alarm signals, its false alarm rate was higher than that of the gastrocnemius, and the advance warning time was too long, reducing the effectiveness of the warning in combat scenarios. These studies ultimately confirmed that placing sensors on the calf gastrocnemius is the optimal solution for predicting G-LOC, effectively eliminating unstable signal sources.

3.3 Development of G-LOC Warning Algorithms and System Implementation

To achieve real-time monitoring of G-LOC and translate it into actual flight safety capabilities, researchers have developed automated discrimination algorithms based on established key physiological features (such as IAV and WL) and constructed hardware systems integrating monitoring, analysis, and active intervention.

regarding warning algorithm development, researchers have focused on converting physiological signal features into computer-executable logic rules. Choi et al. [21] proposed a "2-condition analysis method" based on sliding window technology. This algorithm set two core trigger conditions: first, detecting that the Integrated Absolute Value (IAV) and Waveform Length (WL) show a negative slope for 3 consecutive time windows, with the value in the 3rd window being lower than 70% of the initial value; second, that these two parameters are simultaneously lower than 70% of the initial value for 3 consecutive windows. The significance of this algorithm lies in its first-time quantification of G-LOC warning logic, proving the feasibility of predicting loss of consciousness by monitoring signal attenuation. Building on this, Li et al. verified this method using high-G centrifuge training data from Chinese pilots, confirming its effectiveness. However, to adapt to the physical differences of specific populations and improve warning accuracy, they suggested adjusting the judgment threshold from 70% to 72%.

To further improve algorithm sensitivity and cover different flight scenarios, Kim et al. [22] developed a more comprehensive dual-algorithm system. In addition to the algorithm monitoring muscle endurance decay, they supplemented it with an algorithm for muscle explosive power. This algorithm monitors the "climb rate" of EMG signals during the G-value ascent phase; if the G-load increases but the EMG fails to enhance synchronously, it determines a risk exists and issues an alarm. The combined use of these two algorithms achieved 100% sensitivity in experiments, effectively compensating for the deficiencies of single indicators. Furthermore, Li et al. [20] innovatively proposed the "Load Comparison Method," which performs warning by comparing the ratio changes of EMG parameters between two adjacent loads for the same subject. If the ratio of parameters under high G-load to baseline values continues to decrease, it is regarded as a risk signal. This method utilizes the subject's own baseline data for dynamic calibration, reducing false alarms caused by individual differences and providing a new technical path for G-LOC warning.

In terms of practical system implementation, Wu and Yao[23] designed and realized a complete "Loss of Consciousness Monitoring and Wake-up System." The hardware architecture integrates MPU6050 inertial sensors and EMG sensors, capable of simultaneously monitoring the pilot's head posture (e.g., abnormal nodding) and the contraction state of the calf gastrocnemius in real-time, thereby achieving multi-dimensional state perception. In terms of software interaction logic, they designed a graded intervention mechanism: when the system algorithm determines an abnormal head posture (nodding exceeding a threshold) or EMG signal energy attenuation, it first issues a voice reminder to "Please raise your head" or "Use leg force"; if no feedback action from the pilot is detected within a specified time, the system automatically upgrades to a forced wake-up mode with vibration and high-decibel alarms. Additionally, they developed host computer software based on WiFi communication, realizing real-time data transmission, visualization, and storage functions, facilitating ground personnel to grasp the pilot's status in real-time. Through simulation tests on animal centrifuges (4G, 6G, 8G environments), they verified the operational stability and logical validity of the system in high-overload environments, demonstrating the practical application potential of this technology in shortening pilot in-flight incapacitation time and preventing catastrophic accidents.

4. Conclusion

Comprehensive existing research indicates that Surface Electromyography (sEMG) technology has achieved significant theoretical breakthroughs and engineering progress in the field of G-LOC monitoring and warning. However, the transition of this technology from the laboratory to combat application still faces multiple limitations and challenges:

First, sample size limitations affect the universality of warning models. The subject sample sizes in existing studies are relatively small, and positive samples where G-LOC actually occurs are extremely scarce. This leads to warning thresholds being derived primarily from limited data, necessitating verification in larger populations to address threshold drift caused

by individual physiological differences.

Second, single algorithms lack adaptability to complex flight states. Current warning algorithms mainly target simple continuous high-G processes and are less effective for monitoring G-LOC induced by the Push-Pull Effect (PPE). This is because PPE-induced loss of consciousness primarily stems from rapid blood pressure changes caused by hydrostatics, which has a relatively low correlation with muscle anti-G exertion, causing the "2-condition analysis method" based on EMG attenuation to easily fail in such scenarios.

Furthermore, there are differences between experimental environments and real flight scenarios. Existing system tests are mostly confined to ground centrifuge simulations or low-gravity environments, lacking actual measurement data under complex electromagnetic environments, high-frequency vibrations, and extreme maneuvers in real flight.

To address these issues, future research needs to seek breakthroughs in three dimensions: data accumulation, algorithm fusion, and system integration:

Deepening Data Accumulation and Threshold Refinement: To overcome the problem of sample scarcity, it is necessary to expand the scale of experiments and even consider designing centrifuge animal experiments to obtain richer G-LOC critical data. Through the accumulation of large sample data, warning thresholds for head posture and EMG signals can be more precisely determined, thereby enhancing the robustness of warning models.

Algorithm Optimization and Multi-Sensor Fusion: Algorithms should be further optimized to adapt to different types of acceleration curves (such as PPE). The future trend is to explore multi-sensor fusion technology, combining EMG signals (gastrocnemius, quadriceps, etc.) with EEG, head posture, or ear pulse signals. This multi-modal fusion method can compensate for the defects of single signals, effectively reduce the false alarm rate, and improve adaptability to complex flight states.

System Integration and Combat Transformation: At the system integration level, the future goal is to deeply embed physiological signal monitoring modules into pilots' wearable computers or anti-G equipment. The focus should be on developing lightweight, low-power real-time monitoring terminals and introducing adaptive algorithms to cope with individual differences, ultimately building an intelligent G-LOC protection system capable of adapting to different flight missions and individual characteristics.

References

- [1] Chang, W., Peng, Z., Li, C., et al. (2022). Research progress on physiological early warning indicators and alarm technology for high overload incapacitation. *Academic Journal of Second Military Medical University*, 43(2), 194-200. <https://doi.org/10.16781/j.CN31-2187/R.20211025>
- [2] Yao, Y., Wu, X., & Sun, X. (1999). Mechanism and monitoring of loss of consciousness induced by sustained positive acceleration. *Space Medicine & Medical Engineering*, 12(5), 386-390. <https://doi.org/10.3969/j.issn.1002-0837.1999.05.017>
- [3] Slungaard, E., McLeod, J., Green, N. D. C., et al. (2017). Incidence of G-induced loss of consciousness and almost loss of consciousness in the Royal Air Force. *Aerospace Medicine and Human Performance*, 88(6), 550-555. <https://doi.org/10.3357/AMHP.4752.2017>
- [4] Cao, X. S., Wang, Y. C., Xu, L., et al. (2012). Visual symptoms and G-induced loss of consciousness in 594 Chinese Air Force aircrew—A questionnaire survey. *Military Medicine*, 177(2), 194-198. <https://doi.org/10.7205/milmed-d-11-00003>
- [5] Li, Y., Zhang, T., Deng, L., et al. (2013). Review of EEG changes under high gravitational acceleration and its simulation conditions. *Beijing Biomedical Engineering*, 32, 647-654. <https://doi.org/10.3969/j.issn.1002-3208.2013.06.18>
- [6] Wu, B., Xue, Y., You, G., et al. (2011). Study on prodromal reaction characteristics and warning methods of acceleration-induced loss of consciousness. *Medical Journal of Air Force*, 27, 28-32. <https://doi.org/10.3969/j.issn.2095-3402.2011.01.009>
- [7] Mo, L., Wang, H., He, B., et al. (2018). Design and validation of ear pulse sensor for manned centrifuge training. *Space Medicine & Medical Engineering*, 31, 618-622.
- [8] FLORENCE G, BONNIER R, RIONDET L, et al. Cerebral cortical blood flow during loss of consciousness induced by gravitational stress in rhesus monkeys[J]. *Neurosci Lett*, 2001, 305: 99-102. DOI:10.1016/s0304-3940(01)01818-3
- [9] Cao, Z., Jin, C., Wang, C., et al. (2025). Research on acceleration-induced loss of consciousness warning model based on cerebral oxygen saturation. *Journal of Air Force Medical University*, 46(1), 57-62. <https://doi.org/10.13276/j.issn.2097-1656.2025.01.010>
- [10] SPENCER G S, SMITH R. Exploring the origins of EEG motion artefacts during simultaneous fMRI acquisition: implications for motion artefact correction[J]. *NeuroImage*, 2018, 173: 188-198. DOI: 10.1016/j.neuroimage.2018.02.034.

- [11] ZAWADZKA-BARTCZAK E K, KOPKA L H. Cardiac arrhythmias during aerobic flight and its simulation on a centrifuge[J]. *Aviat Space Environ Med*, 2011, 82(6): 599-603. DOI: 10.3357/ASEM.2971.2011.
- [12] ROMERO J, FERLINI A, SPATHIS D, et al. OptiBreathe: an earable-based PPG system for continuous respiration rate, breathing phase, and tidal volume monitoring[C]//Proc 25th Int Workshop on Mobile Computing Systems and Applications. ACM, 2024: 99-106. DOI: 10.1145/3638550.3639567.
- [13] WANG F, JIN P, FENG Y, et al. Flexible Doppler ultrasound device for the monitoring of blood flow velocity[J]. *Sci Adv*, 2021, 7(44): eabi9283. DOI: 10.1126/sciadv.abi9283.
- [14] LIAN C, LI P, WANG N, et al. Comparison of basic regional cerebral oxygen saturation values in patients of different ages: a pilot study[J]. *J Int Med Res*, 2020, 48(8): 0300060520936800. DOI: 10.1177/0300060520936800.
- [15] CHOI B, KIM D, KIM M, et al. Effectiveness of EMG in development of G-induced loss of consciousness (G-LOC) warning system[C]//Proc Int Conf Biomed Eng Syst. Avestia, 2014: 1-4.
- [16] Farina D, Merletti R, Enoka R M. The extraction of neural strategies from the surface EMG. *Journal of Applied Phys-iology*, 2004, 96(4): 1486–1495.
- [17] Chu J U, Moon I, Lee Y J, Kim S K, Mun M S. A supervised feature-projection-based real-time EMG pattern recog-nition for multifunction myoelectric hand control. *IEEE/ASME Transactions on Mechatronics*, 2007, 12(3): 282–290
- [18] Cornwall, M. W., & Krock, L. P. (1992). Electromyographic activity while performing the anti-G straining maneuver during high sustained acceleration. *Aviation, space, and environmental medicine*, 63(11), 971–975.
- [19] KIM S, KIM D, CHO Y, et al. Analysis on electromyogram (EMG) signals by body parts for G-induced loss of con-sciousness (G-LOC) prediction[J]. *J Korea Inst Mil Sci Technol*, 2017, 20(1): 119-128. DOI: <https://doi.org/10.9766/KIMST.2017.20.1.119>
- [20] Li, Y., Yang, J., Li, B., et al. (2024). Effectiveness of EMG changes under centrifuge G-load for G-LOC early warning. *Medical Equipment*, 45(12), 25-31. <https://doi.org/10.19745/j.1003-8868.20242431>
- [21] CHOI B, LEE Y, CHO T, et al. Detection of G-Induced Loss of Consciousness (G-LOC) prognosis through EMG mon-itoring on gastrocnemius muscle in flight[C]//2015 37th Annual In-ternational Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), August 25-29, 2015, Milan. New York: IEEE□2015: 7 007-7 010.
- [22] Kim, S., Cho, T., Lee, Y., Koo, H., Choi, B., & Kim, D. (2017). G-LOC Warning Algorithms Based on EMG Features of the Gastrocnemius Muscle. *Aerospace medicine and human performance*, 88(8), 737–742. <https://doi.org/10.3357/AMHP.4781.2017>.
- [23] Wu, C., & Yao, Y. (2024). Loss of consciousness monitoring and wake-up system based on head posture and EMG signals. *Academic Journal of Naval Medical University*, 45(11), 1425-1433. <https://doi.org/10.16781/j.CN31-2187/R.20230305>.