



AI-driven wearable technologies for brain tumor risk assessment among professional athletes: a systematic review

Tecnologías portátiles impulsadas por inteligencia artificial para la evaluación del riesgo de tumores cerebrales en atletas profesionales: una revisión sistemática

Authors

Azhar Tursynova¹
Jandos Mergenbayuly Yessirkepov²

¹ Al-Farabi Kazakh National University (Kazakhstan)

² International University of Tourism and Hospitality (Kazakhstan)

Corresponding author:
Azhar Tursynova
azhar.tursynova1@gmail.com

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Abstract

Introduction: the study addressed the emerging role of artificial intelligence combined with wearable technologies in the assessment of brain tumor risk among professional athletes. the importance of early detection and continuous monitoring was highlighted.

Objective: the purpose of this study was to systematically review recent advances in wearable systems enhanced by artificial intelligence and to critically evaluate their applicability, effectiveness, and potential benefits for neurological risk assessment in professional athletes, with emphasis on early detection, monitoring, and preventive strategies.

Methodology: a systematic review methodology was employed, analyzing recent studies on wearable biosensors, physiological monitoring techniques, and artificial intelligence algorithms. collected data were evaluated and synthesized comparatively to identify patterns, assess applicability, and highlight advancements in neurological risk assessment.

Results: the study demonstrated that wearable devices integrated with artificial intelligence enabled reliable detection of early neurological abnormalities, effective monitoring of concussion-related risks, and comprehensive assessment of fatigue, recovery, and stress-related biomarkers in professional athletes, enhancing overall neurological health management.

Discussion: the findings confirmed that AI-based wearables aligned with previous evidence in medical diagnostics, while also extending applications to sports medicine. the integration of multimodal sensing and real-time analytics was emphasized.

Conclusions: AI-driven wearable technologies offer a pathway toward proactive, personalized risk assessment in athletes, with potential to enhance health, safety, and performance.

Keywords

Artificial intelligence; wearable technologies; brain tumor; professional athletes; electroencephalogram; sports medicine; health monitoring.

Resumen

Introducción: el estudio abordó el papel emergente de la inteligencia artificial combinada con tecnologías portátiles en la evaluación del riesgo de tumores cerebrales en atletas profesionales. se destacó la importancia de la detección temprana y el monitoreo continuo.

Objetivo: el propósito de este estudio fue revisar de manera sistemática los avances recientes en sistemas portátiles mejorados por inteligencia artificial y evaluar críticamente su aplicabilidad, eficacia y beneficios potenciales para la evaluación del riesgo neurológico en atletas profesionales, con énfasis en la detección temprana, el monitoreo y las estrategias preventivas.

Metodología: se aplicó una metodología de revisión sistemática, analizando investigaciones recientes sobre biosensores portátiles, técnicas de monitoreo fisiológico y algoritmos de inteligencia artificial. los datos recopilados fueron evaluados y sintetizados comparativamente para identificar patrones, valorar su aplicabilidad y resaltar avances en la evaluación del riesgo neurológico.

Resultados: el estudio demostró que los dispositivos portátiles integrados con inteligencia artificial permitieron una detección confiable de anomalías neurológicas tempranas, un monitoreo eficaz de riesgos relacionados con conmociones y una evaluación integral de biomarcadores de fatiga, recuperación y estrés en atletas profesionales, mejorando la gestión neurológica.

Discusión: los hallazgos confirmaron que los dispositivos portátiles basados en ia se alinearon con la evidencia previa en diagnósticos médicos, al mismo tiempo que ampliaron las aplicaciones a la medicina deportiva. se destacó la integración de sensores multimodales y el análisis en tiempo real.

Conclusiones: las tecnologías portátiles impulsadas por ia ofrecen una vía hacia una evaluación proactiva y personalizada del riesgo en atletas, con potencial para mejorar la salud, la seguridad y el rendimiento.

Palabras clave

Inteligencia artificial; tecnologías portátiles; tumor cerebral; atletas profesionales; electroencefalograma; medicina deportiva; monitoreo de la salud.

Introduction

Brain tumors represent one of the most severe neurological disorders due to their high morbidity and mortality, often exacerbated by late-stage diagnosis and limited treatment windows (Birla et al., 2025). In professional athletes, the risks associated with brain tumors are compounded by intensive physical demands, recurrent head impacts, and exposure to high-stress environments that may accelerate neurological decline (Olawade et al., 2025). Early detection and continuous monitoring are therefore critical, as even subtle cognitive and physiological impairments can undermine both health outcomes and athletic performance (Zheng et al., 2025). Traditional diagnostic modalities such as MRI and CT remain indispensable, yet they are costly, episodic, and impractical for routine use among athletes, necessitating more portable and accessible alternatives (Dileepkumar et al., 2025).

In recent years, wearable health technologies have emerged as transformative tools for continuous, non-invasive monitoring of physiological and neurological parameters (Yao et al., 2025). Devices capable of measuring EEG, heart rate variability (HRV), blood oxygenation, or gait patterns can provide real-time insights into neurological function (Omarov et al., 2024; Desai et al., 2024). When coupled with advances in miniaturization and wireless communication, wearables can be seamlessly integrated into athletes' daily training and competition environments (Palermi et al., 2024). Importantly, these devices generate large-scale multimodal datasets that capture subtle variations in brain and body function, offering opportunities for early anomaly detection. Despite these advantages, raw sensor data is often noisy and difficult to interpret without computational augmentation (Kumar et al., 2025).

Artificial intelligence (AI) has thus become central to the interpretation of wearable data for brain health monitoring (Wan et al., 2025). Machine learning and deep learning algorithms enable automated feature extraction, classification, and prediction of neurological abnormalities that may indicate elevated tumor risk (Anghelescu et al., 2025). AI has already shown promise in neuroimaging analysis, providing higher sensitivity for tumor detection compared to conventional methods (Yadav et al., 2025). Extending these techniques to wearable-based data opens the possibility of continuous, real-time monitoring, thereby addressing the limitations of episodic imaging and clinical evaluations. Furthermore, AI-driven approaches can personalize risk models, accounting for athlete-specific physiology and performance baselines (Miotto et al., 2018).

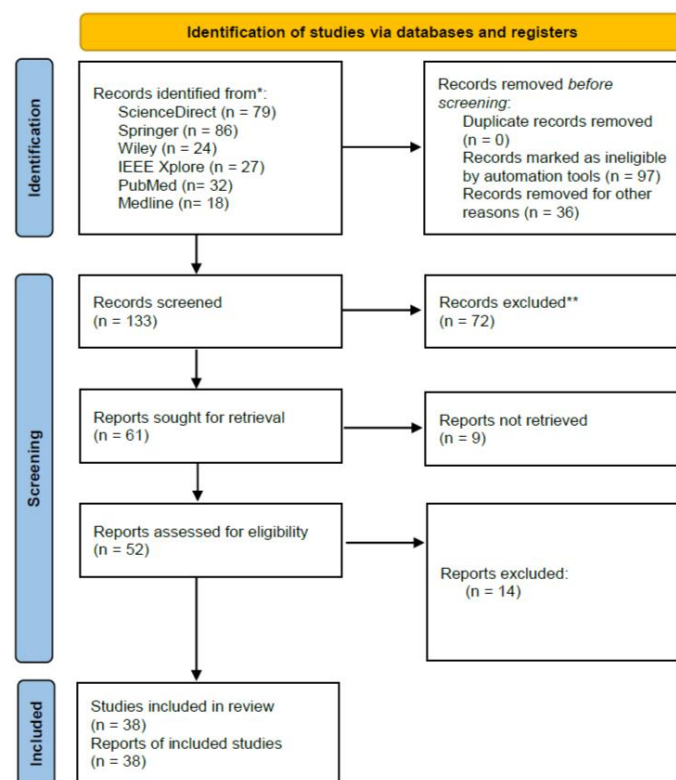
The convergence of wearable technologies and AI-driven analytics presents a unique opportunity for proactive brain tumor risk assessment in professional athletes. By enabling longitudinal monitoring, these systems could support early intervention strategies, improve prognosis, and reduce long-term neurological impairments (Gupta et al., 2024). However, challenges remain, including issues of sensor reliability, algorithmic interpretability, and data privacy in high-stakes sports contexts (Guan et al., 2025). This review aims to synthesize current progress in AI-driven wearable technologies for brain tumor risk assessment, examine their applications in athletic populations, and identify future research directions toward clinical translation and practical adoption in sports medicine.

The realization of this study is justified by the growing need to establish effective, non-invasive, and continuous monitoring strategies that safeguard the neurological health of professional athletes. This population, due to its exposure to intense physical activity, repeated cranial impacts, and high-performance demands, represents a group particularly vulnerable to the development or exacerbation of neurological conditions, including brain tumors. The contribution of this research extends beyond sports medicine, offering a social benefit by promoting the early detection of potentially life-threatening diseases through accessible and data-driven technologies. Moreover, the integration of artificial intelligence with wearable monitoring systems can support public health initiatives focused on prevention and personalized care, bridging the gap between clinical diagnostics and daily life applications. Therefore, this review not only addresses a scientific need but also advances a human-centered approach to athlete welfare and long-term neurological safety.

Materials and Methods

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological rigor and transparency. The identification of studies was performed through a comprehensive search of multiple academic databases, including ScienceDirect (n = 79), Springer (n = 86), Wiley (n = 24), IEEE Xplore (n = 27), PubMed (n = 32), and Medline (n = 18). This initial search yielded a total of 266 records. Prior to screening, automated and manual processes were applied to remove ineligible records, including those flagged by automation tools (n = 97) and those excluded for other reasons (n = 36), resulting in 133 studies entering the screening stage (Figure 1).

Figure 1. PRISMA flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies in the review.



During the screening process, titles and abstracts were independently reviewed to assess relevance to the predefined inclusion criteria, which focused on AI-driven wearable technologies and their applications in neurological health assessment or brain tumor risk evaluation. Of the 133 records screened, 72 were excluded based on irrelevance, leaving 61 reports sought for retrieval. Nine records could not be retrieved due to accessibility issues, and the remaining 52 full-text reports were assessed for eligibility. Following detailed evaluation, 14 reports were excluded due to insufficient methodological quality or lack of direct relevance to the research scope.

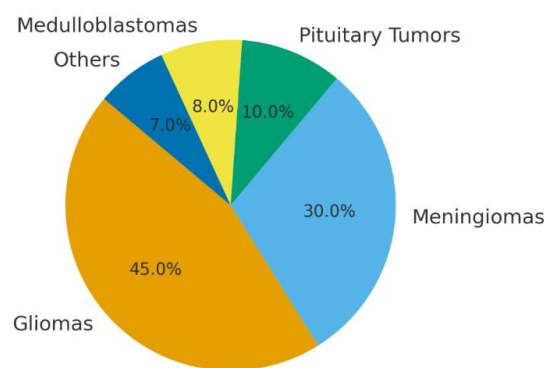
Ultimately, 38 studies were included in this review (Figure 1). These studies were analyzed in terms of their methodological approaches, wearable technology types, AI algorithms implemented, and applicability to brain tumor risk assessment among professional athletes. The selection process, illustrated in the PRISMA flow diagram, highlights the rigorous multi-stage filtering employed to ensure that only high-quality, thematically relevant studies contributed to the final synthesis. This structured approach provides a robust foundation for examining the intersection of artificial intelligence, wearable technology, and sports-related neurological health.

Results

Brain Tumors and Athletes: Clinical and Physiological Context

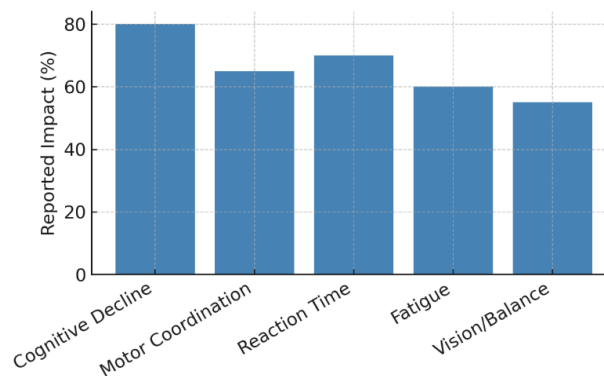
Brain tumors encompass a heterogeneous group of neoplasms, with gliomas, meningiomas, pituitary tumors, and medulloblastomas being among the most clinically relevant types (Jawed et al., 2025). Gliomas represent the majority of malignant tumors and are characterized by their aggressive infiltration into brain tissue, whereas meningiomas, although often benign, can exert significant pressure on adjacent structures, leading to neurological dysfunction (Ganti et al., 2025). Pituitary tumors may alter endocrine regulation, which can indirectly affect athletic performance, while medulloblastomas, though less frequent in adults, carry high risks due to their impact on cerebellar function (Singh et al., 2024). The relative distribution of these tumor types relevant to athletes is illustrated in Figure 2, which highlights the predominance of gliomas and meningiomas in clinical contexts (Wang et al., 2025).

Figure 2. Distribution of brain tumor types relevant to athletes.



Professional athletes face unique physiological demands that may amplify the consequences of neurological pathology. High-intensity training, repetitive head impacts, and exposure to concussive and sub-concussive events in contact sports have been linked to heightened vulnerability to central nervous system disorders (Al-Shareeda et al., 2025). Moreover, the physiological stress induced by prolonged competition and overtraining can influence immune and metabolic pathways, potentially exacerbating tumor progression or reducing the resilience of neurological systems (Omarov et al., 2024; Muse & Topol, 2024). These risks are not uniform across sports; for example, combat athletes may face direct cranial trauma, while endurance athletes experience chronic physiological stress that may indirectly influence neurological health (Tóth 2024).

Figure 3. Neurological and physical implications of brain tumors in athletes.



The clinical manifestations of brain tumors in athletes are often subtle and may overlap with sport-related fatigue, concussions, or stress-induced cognitive impairment (Miller et al., 2020). Symptoms such as slowed reaction time, motor coordination deficits, memory decline, and balance disturbances

can remain undetected until tumor progression reaches advanced stages (Shen et al., 2020). The cumulative neurological and physical performance implications are summarized in Figure 3, which demonstrates how cognitive decline, motor impairments, and reduced reaction times significantly undermine athletic performance (Zhang & Meng, 2025).

Despite advances in neuroimaging, conventional diagnostic modalities such as MRI and CT remain episodic and resource-intensive, making them ill-suited for proactive monitoring in athlete populations (Junior et al., 2025). Additionally, standard clinical evaluations are limited by their reliance on subjective symptom reporting and infrequent follow-ups (Tzenios & Wong, 2025). These gaps underscore the necessity of integrating advanced wearable technologies with AI-driven analytics to facilitate early, real-time detection of tumor-related anomalies. Such innovations could transform the current paradigm of neurological care for athletes, moving from reactive diagnosis to proactive risk assessment and intervention.

Wearable Technologies in Healthcare

Wearable technologies have undergone a remarkable transformation from simple mechanical devices to highly sophisticated digital health companions, redefining how physiological and neurological monitoring is conducted in both clinical and athletic contexts. The historical trajectory of wearables, illustrated in Figure 4, shows an evolution beginning with basic timekeeping instruments in the eighteenth century and progressing through pivotal innovations such as calculator watches, pagers, and early fitness trackers like the Fitbit, culminating in today's advanced smartwatches and augmented reality glasses. This progression reflects a broader technological paradigm shift driven by miniaturization of sensors, wireless connectivity, and advances in biosignal acquisition, enabling devices to transition from passive lifestyle accessories to integral tools in healthcare delivery. Modern wearables are now capable of capturing multimodal data streams including electroencephalography (EEG), electrocardiography (ECG), heart rate variability (HRV), blood oxygenation, gait patterns, and motion analysis providing real-time insights into neurological and cardiovascular health. Importantly, these innovations are not merely incremental but represent a fundamental change in health monitoring philosophy, moving from episodic, clinic-centered assessments toward continuous, personalized, and proactive healthcare. By contextualizing wearable technologies within this historical framework, it becomes clear that their integration into healthcare is not accidental but rather the result of decades of iterative innovation that continues to shape the future of brain health assessment and athlete-centered monitoring.

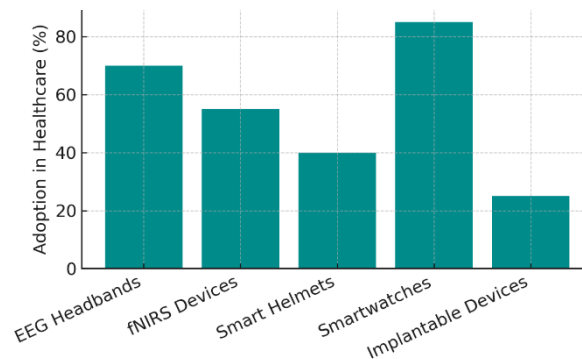
Figure 4. Wearable Technologies in Healthcare.



The evolution of wearable biosensors has transformed the landscape of healthcare by enabling continuous, non-invasive monitoring of physiological and neurological functions. Early developments were limited to pedometers and heart rate monitors, but advances in microelectronics, wireless communication, and sensor miniaturization have facilitated the creation of highly sophisticated devices capable of measuring complex biological signals (Nasb et al., 2025). Today, wearable devices are increasingly uti-

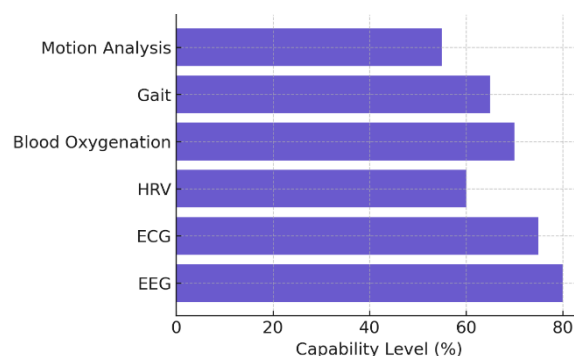
lized in clinical and athletic populations for real-time monitoring of brain activity, cardiovascular function, and movement dynamics, offering unprecedented opportunities for early disease detection and personalized healthcare management (Jawed et al., 2025).

Figure 5. Adoption of Different Wearable Technologies in Healthcare.



Several categories of wearable technologies are now integral to healthcare applications. EEG headbands and fNIRS devices allow for continuous brain monitoring by measuring electrical and hemodynamic activity, respectively, while smart helmets are being adapted for impact detection and concussion assessment in athletes (Narayanan et al., 2024). Consumer-oriented devices such as smartwatches integrate ECG and HRV monitoring, bridging clinical and everyday health contexts (Awujoola et al., 2024). Additionally, implantable or semi-invasive devices provide long-term biosignal acquisition with higher accuracy but raise concerns regarding patient compliance and safety (Jun et al., 2025). The adoption levels of these technologies in healthcare are depicted in Figure 5, highlighting the predominance of smartwatches and EEG-based wearables.

Figure 6. Physiological and Neurological Data Captured by Wearables.



Wearable devices capture a wide range of data streams, including EEG, ECG, HRV, blood oxygenation, gait, and motion dynamics, each offering unique insights into neurological and physiological status (Leeba & James, 2025). For example, EEG monitoring can detect abnormal neural oscillations, while HRV provides information on autonomic nervous system function relevant to stress and recovery (Patel et al., 2022). Similarly, gait and motion analysis have been applied to detect subtle motor deficits associated with neurodegenerative disorders (Shafik et al., 2024). The relative capabilities of wearables in capturing these data types are summarized in Figure 6, demonstrating that EEG and ECG remain the most established modalities, while motion analysis is gaining traction in athletic and clinical research.

Despite their potential, wearable devices for neurological applications face significant limitations. Data accuracy may be compromised by motion artifacts, electrode placement, or environmental interference, especially in high-intensity athletic settings (Mennella, 2024). Furthermore, the integration of large-scale, multimodal data streams requires advanced computational frameworks, often relying on cloud or edge AI systems that raise concerns regarding latency, interpretability, and data privacy (Jena et al.,

2025). Nevertheless, the growing sophistication of wearable technologies, coupled with advances in AI-driven analytics, continues to strengthen their role in healthcare and sports medicine, positioning them as pivotal tools for proactive brain health monitoring.

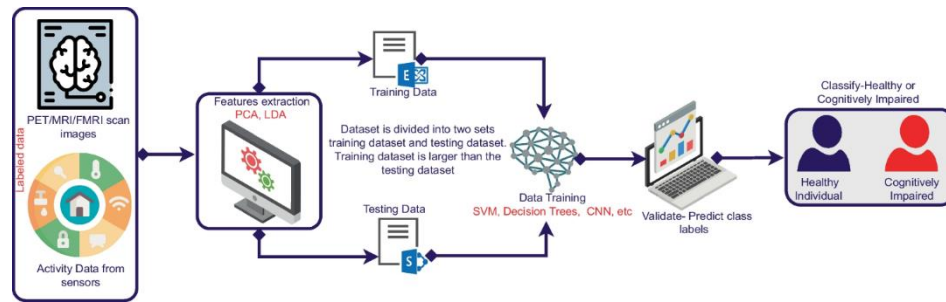
Artificial Intelligence in Brain Health Assessment

The integration of wearable sensor technologies with artificial intelligence offers a transformative approach for early brain tumor risk assessment. As illustrated in Figure 8, the process begins with multi-modal data collection from wearable sensors, including EEG, fNIRS, HRV, sleep monitoring, and motion tracking. These raw physiological and behavioral signals undergo systematic acquisition and preprocessing before being transformed into meaningful features such as EEG rhythms, HRV variability indices, and reaction time metrics. Machine learning and deep learning models—ranging from traditional SVMs to advanced CNN and RNN architectures—are then applied to detect subtle neurocognitive changes indicative of early pathology. The deployment of these models on edge or cloud infrastructures enables real-time analysis and continuous feedback, creating a closed-loop system for risk monitoring and timely interventions. Artificial intelligence (AI) has rapidly emerged as a transformative force in medical diagnostics, particularly in the domain of brain health, where the complexity of neurological disorders demands highly precise and scalable analytical methods. Traditional machine learning (ML) techniques such as support vector machines (SVM), decision trees, and random forests have been extensively applied to brain-related datasets, offering robust classification capabilities for structured data (Ahmed et al., 2023). However, the advent of deep learning (DL) architectures, including convolutional neural networks (CNNs) and recurrent neural networks (RNNs), has significantly advanced the field by enabling automated feature learning from high-dimensional imaging and physiological signals (Sheng et al., 2025). More recently, hybrid approaches that integrate ML and DL pipelines have demonstrated promise in enhancing diagnostic accuracy while addressing limitations such as data imbalance and interpretability (Omarov et al., 2023; Taherdoost 2024). These methodological advances underscore AI's potential to deliver not only diagnostic precision but also real-time adaptability in diverse clinical and athletic contexts.

Feature extraction and classification remain central to the application of AI in brain health monitoring. Brain-related health data, such as EEG, ECG, and fNIRS signals, contain complex temporal and spatial patterns that require sophisticated computational techniques for meaningful interpretation (Singh & Kaunert, 2025). Preprocessing methods such as wavelet transforms, principal component analysis (PCA), and autoencoders have been used to isolate relevant biomarkers, which are then classified using supervised and unsupervised algorithms (Arega & Sharma, 2024; Alavinejad et al., 2025). For instance, AI-driven EEG analysis can detect subtle tumor-related oscillations that escape conventional diagnostic assessments (Chaithra et al., 2024). By automating these processes, AI reduces clinician burden and ensures higher sensitivity to early pathological changes, which is especially crucial for populations like athletes, where even minor impairments can affect performance and safety.

In neuroimaging, AI has demonstrated exceptional capabilities in enhancing the diagnostic yield of MRI, CT, and PET scans. CNN-based models have achieved state-of-the-art performance in tumor segmentation, volumetric analysis, and progression prediction, often outperforming radiologists in detection speed and accuracy (Almansour, 2025). Integration of neuroimaging with wearable devices further strengthens diagnostic insights by linking episodic imaging findings with continuous physiological monitoring (Farkas et al., 2025). For example, wearable-derived HRV and EEG data can be analyzed alongside MRI features to build comprehensive risk profiles, offering both macrostructural and microphysiological perspectives of brain health. Such multimodal integration represents a step toward holistic precision medicine, where AI synthesizes diverse datasets into actionable knowledge.

Figure 7. Artificial Intelligence for Cognitive Health Assessment.

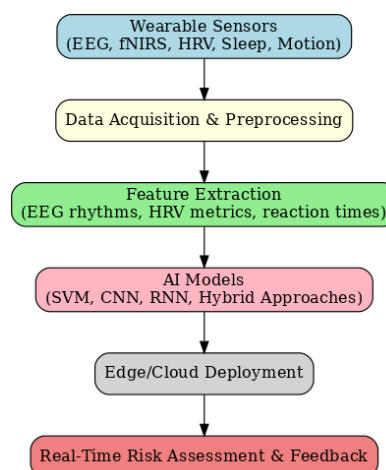


Beyond imaging, AI excels in anomaly detection within physiological signals, enabling real-time monitoring and early intervention. Algorithms such as autoencoders, long short-term memory (LSTM) networks, and generative adversarial networks (GANs) can detect deviations from individual baselines, signaling potential tumor progression or neurological dysfunction before clinical symptoms manifest (Komalasari, 2024). These approaches are particularly valuable in wearable technologies, where continuous data collection demands scalable and adaptive analysis frameworks (Rahman et al., 2022). The advantages of AI for continuous, real-time risk assessment include early detection, personalized health monitoring, and rapid decision support, making it indispensable in sports medicine and neurological care. As these systems evolve, the integration of explainable AI (XAI) techniques will further enhance clinician trust, ensuring that AI-driven diagnostics are transparent, interpretable, and aligned with ethical standards in healthcare. The workflow of AI-driven brain health diagnostics is illustrated in Figure 7, which demonstrates how multimodal data from imaging and sensors undergo feature extraction, training, and classification to differentiate between healthy individuals and those with cognitive impairment. This schematic highlights the integration of machine learning and deep learning models in producing accurate and clinically meaningful outcomes.

Wearable Sensors

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Figure 8. AI-Wearable Integration Pipeline for Brain Tumor Risk Assessment.



Signal-based approaches represent one of the most promising applications of wearable technologies in brain tumor risk assessment. Wearable electroencephalography (EEG) headbands and functional near-infrared spectroscopy (fNIRS) devices enable continuous recording of brain activity, allowing AI algorithms to detect abnormal oscillatory patterns and hemodynamic responses that may precede clinical symptoms (Li & Xu, 2021). By leveraging machine learning and deep learning techniques for feature extraction and classification, these systems can identify subtle deviations in brain function, thus enabling early screening of at-risk athletes in real-world environments.

Physiological monitoring through wearables expands the diagnostic landscape by capturing autonomic and behavioral biomarkers associated with neurological impairment. Parameters such as heart rate variability (HRV), sleep architecture, cognitive load, and reaction times have been increasingly recognized as indirect indicators of brain health (Karibzhanova et al., 2025). AI-driven models can analyze these multimodal physiological datasets to uncover hidden patterns that correlate with tumor-related cognitive or metabolic disruptions, thereby complementing direct neural monitoring methods.

In addition to physiological signals, neurocognitive performance tracking has become feasible through gamified wearable platforms and interactive applications. By embedding cognitive tasks into wearable ecosystems, athletes' attention, memory, and reaction profiles can be continuously monitored (Podder et al., 2025). AI models can then process this performance data to detect subtle impairments that might otherwise go unnoticed in standard neurological evaluations. Such an approach is particularly valuable in sports, where small declines in cognitive agility may significantly affect performance and safety.

Central to the effectiveness of AI-driven wearables is the development of robust integration pipelines. These pipelines typically include stages of data acquisition, preprocessing, feature engineering, model training, and deployment on edge or cloud platforms (Edward et al., 2025; Kumari et al., 2023). Edge computing allows for low-latency processing directly on the wearable device, while cloud infrastructures enable large-scale analytics and model refinement. The pipeline ensures that both raw sensor signals and derived biomarkers are systematically transformed into clinically relevant insights, enhancing reliability and interpretability.

Case studies and pilot projects further demonstrate the feasibility of this approach. For example, AI-powered EEG headsets have been tested in athletic populations for detecting early neurological abnormalities, while smartwatch-based HRV monitoring has been linked to predictive models of cognitive decline (Badiger et al., 2025). Although still in early stages, such pilot deployments underscore the translational potential of AI-driven wearable systems in moving brain tumor risk assessment from controlled laboratory settings into dynamic, real-world sports environments.

AI-Driven Wearable Technologies for Brain Tumor Risk Assessment

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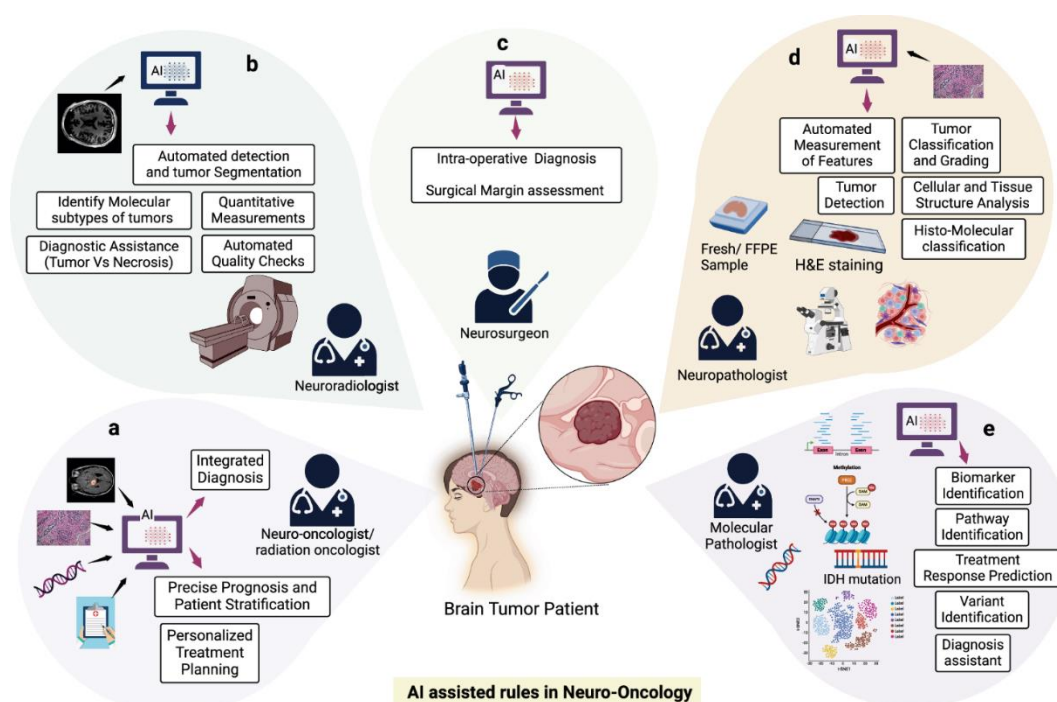
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Applications for Professional Athletes

AI-driven wearable technologies offer significant potential for risk assessment during training and competitions, providing athletes and medical professionals with continuous insights into neurological health. By integrating multimodal signals such as EEG, fNIRS, and HRV into advanced AI pipelines, these systems can identify subtle biomarkers of neurological stress or early tumor-related abnormalities before they manifest as clinical symptoms. This is particularly critical in elite sports, where marginal declines in cognitive agility or reaction time can directly impact performance and safety. As illustrated in Figure 9, AI-assisted frameworks facilitate integrated diagnosis, prognosis, and treatment planning, suggesting that similar methodologies can be adapted for real-time monitoring in athletic populations.

Figure 9. AI-assisted roles in neuro-oncology across multidisciplinary clinical practices.



Another vital application is the monitoring of concussion-related injuries and their potential connection to tumor progression. Contact sports such as football, boxing, and hockey expose athletes to repetitive head trauma, which may exacerbate underlying neurological vulnerabilities. Wearable devices equipped with accelerometers and gyroscopic sensors can detect concussive impacts, while AI algorithms analyze longitudinal datasets to distinguish between transient trauma-related changes and more persistent neurological anomalies indicative of tumor growth. Figure 9 highlights how AI assists neuropathologists and neuroradiologists in differentiating between tumor and necrosis, a process that could

be translated into sports contexts to differentiate between post-traumatic injury and tumor-related pathology.

Wearables also enable the monitoring of fatigue, recovery, and stress biomarkers as indirect indicators of brain health. Parameters such as HRV, sleep quality, cortisol levels, and reaction times provide valuable insights into the athlete's neurological resilience and capacity for recovery. AI models can detect deviations from individualized baselines, offering early warnings of cognitive decline or potential tumor-related impairments. This personalized approach to monitoring aligns with the precision medicine strategies depicted in Figure 9, where AI facilitates patient stratification and tailored treatment planning, underscoring the translational value of these technologies in optimizing athlete health and performance.

Finally, wearables function as preventive screening tools in high-risk sports, serving as a first line of defense for early tumor detection. In sports with high rates of cranial injury, continuous monitoring through smart helmets, EEG headbands, or integrated biosensors may identify anomalies long before they appear on conventional neuroimaging. By leveraging AI-assisted diagnostic pipelines similar to those used in neuro-oncology, sports medicine can transition from reactive management of symptomatic athletes to proactive risk reduction strategies. This paradigm shift emphasizes the crucial role of AI-driven wearables in safeguarding the neurological well-being of athletes while extending their professional longevity.

Discussion

Challenges and Limitations

Despite the promising potential of AI-driven wearable technologies for brain tumor risk assessment, several technical limitations remain significant barriers to widespread adoption. Sensor accuracy and data reliability are persistent concerns, particularly in dynamic environments such as professional sports where motion artifacts, electrode displacement, and environmental interference can degrade signal quality. Noisy datasets present challenges for real-time monitoring, often necessitating complex pre-processing pipelines that increase computational burden and may compromise responsiveness. Furthermore, latency in real-time processing remains a limitation when integrating multimodal data streams on edge devices, where hardware constraints restrict model complexity and energy efficiency. These factors collectively hinder the seamless translation of wearable-based monitoring into reliable clinical-grade diagnostics, underscoring the need for advancements in both hardware engineering and adaptive signal processing methodologies.

In parallel, AI-specific challenges complicate the effectiveness and acceptance of wearable-based systems. Data scarcity and imbalance, especially in rare conditions such as brain tumors among athletes, limit the generalizability of models and increase the risk of overfitting. Interpretability of AI models remains another major obstacle, as black-box predictions raise concerns for clinicians and limit trust in automated decision-making. Ethical issues, including privacy, data ownership, and potential misuse of sensitive health information, further complicate deployment in high-stakes athletic environments. Athlete-specific challenges such as compliance, comfort, and willingness to adopt wearables also impact long-term feasibility, particularly in sports where performance and ergonomics take precedence. Moreover, regulatory and clinical validation gaps remain substantial, as few wearable-AI systems have undergone rigorous trials or received approval for use in medical or sports medicine contexts. Addressing these limitations will require a multidisciplinary approach, combining technical innovation, ethical governance, and policy frameworks to ensure that AI-driven wearables are both effective and trustworthy in real-world applications.

Future Directions

The future of AI-driven wearable technologies for brain tumor risk assessment lies in the development of next-generation systems that are increasingly miniaturized, multimodal, and seamlessly integrated into athletes' daily environments. Advances in nanotechnology and flexible electronics will enable the creation of ultra-lightweight, unobtrusive wearables capable of continuously capturing neurological, cardiovascular, and behavioral data without disrupting performance. Multimodal sensing will expand

beyond EEG and HRV to incorporate blood biomarkers, metabolic indices, and ocular dynamics, while integration with brain–computer interface (BCI) technologies may provide direct access to neural activity at an unprecedented resolution. Such systems could allow early detection of tumor-related abnormalities before they manifest clinically, offering a paradigm shift from episodic imaging to continuous, real-time surveillance. Complementing hardware advancements, athlete-specific diagnostic models trained on large, longitudinal datasets will enable personalized baselines, accounting for sport type, training intensity, and individual physiology. These precision models will enhance the sensitivity of risk assessment and create opportunities for predictive monitoring tailored to the unique demands of high-performance sports.

Alongside technological innovation, the future will also depend on the evolution of computational and policy frameworks that support secure, real-time deployment of wearable monitoring systems. Edge AI and federated learning architectures hold particular promise, as they allow advanced analytics to be performed locally on devices or distributed networks, minimizing latency and safeguarding sensitive health data. Beyond signal processing, integrating genomics and multi-omics datasets with wearable-derived signals will provide a holistic view of athlete health, combining genetic predispositions with dynamic physiological monitoring to refine tumor risk stratification. However, realizing this vision requires not only technical progress but also pathways toward clinical adoption and policy integration in sports medicine. Collaboration among clinicians, sports organizations, and regulatory bodies will be essential to establish standards for data quality, validation, and ethical use. Ultimately, the translation of AI-driven wearable technologies into practice will depend on striking a balance between innovation and governance, ensuring that these systems not only advance early tumor detection but also align with broader goals of athlete safety, privacy, and career longevity.

Conclusion

The integration of artificial intelligence with wearable technologies represents a transformative opportunity for advancing brain tumor risk assessment among professional athletes. By combining multimodal biosensors with machine learning and deep learning algorithms, these systems offer unprecedented capabilities for early detection, continuous monitoring, and personalized health management. Unlike conventional diagnostic tools that are episodic and resource-intensive, AI-driven wearables provide real-time, adaptive insights into neural and physiological states, enabling proactive interventions that may safeguard both health and athletic performance. Moreover, applications extend beyond tumor detection to encompass concussion monitoring, fatigue assessment, and preventive screening in high-risk sports, highlighting their broader value in sports medicine. Nevertheless, significant challenges remain, including technical limitations of sensor accuracy, AI-specific issues such as data scarcity and interpretability, and ethical concerns around privacy and clinical validation. Future directions point toward miniaturized, multimodal devices integrated with brain–computer interfaces, federated learning for secure analytics, and athlete-specific diagnostic models tailored to the unique demands of professional sport. Ultimately, successful translation into practice will depend on interdisciplinary collaboration between engineers, clinicians, policymakers, and sports organizations to ensure that innovation aligns with clinical efficacy, ethical governance, and athlete welfare. In this convergence lies the promise of precision, safety, and longevity in athletic careers.

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Authors' and translators' details:

Azhar Tursynova
Jandos Mergenbayuly Yessirkepov

azhar.tursynova1@gmail.com
jandos.esirkepov@iuth.edu.kz

Author
Author

