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Sleep Biomarkers: New Approaches to Sleep Monitoring at Home

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Abstract: Objectives: A comprehensive review of modern wearable electroencephalography (EEG) systems for home sleep monitoring was conducted, integrating technological and behavioral aspects. Based on an analysis of form factors, materials, and classification algorithms—long short-term memory (LSTM) networks, Random Forest, and convolutional neural networks (CNNs)—the main advances in rigid and flexible headbands, tattoo patches, and in-ear devices were identified. Concurrently, the evolution of consumer perceptions of wellness services was examined, shifting from aesthetics to data-driven resilience. The concept of "emotional ergonomics" was proposed to personalize interfaces, ensure algorithmic transparency, and enhance user emotional comfort.

Methods: The methodology for conducting a systematic review and triangulating literature and user data was substantiated. Scientific gaps in the standardization of wearable EEG device validation were highlighted, and prospects for integrating multisensory platforms and AI-driven analytics to improve monitoring accuracy and user acceptance were outlined.

Findings: The findings are expected to interest researchers in somnology and translational medicine who seek to integrate molecular and physiological indicators with artificial intelligence algorithms to enhance the accuracy of sleep disorder diagnosis and prognosis. Moreover, these insights will be valuable to developers of wearable biometric sensors and digital health platforms, as well as to regulatory experts shaping safety and efficacy standards for remote monitoring technologies.

The **scientific novelty** consists in the introduction, for the first time, of a combined concept of "emotional ergonomics" for sleep devices, integrating the hardware and software characteristics of wearable EEG sensors with contemporary consumers' demands for transparency in validation, personalization, and a comfortable user experience in the post-pandemic period.

Keywords: sleep, wearable EEG, home monitoring, emotional ergonomics, wellness.

1. Introduction

Sleep is a key biomarker of physical and mental health, influencing the function of all body systems and overall quality of life. Insufficient sleep duration and fragmentation are associated with an increased risk of hypertension, cardiovascular and metabolic disorders, reduced cognitive performance, and impaired emotional well-being. Polysomnography (PSG), the traditional method for assessing sleep, remains the gold standard; however, its complexity, high cost (USD 1500–2000 per night in the United States), requirement for qualified personnel, and artificial clinical setting limit its broad application [1].

The article **aims** to analyze novel methods of home-based sleep monitoring.

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The **author's hypothesis** posits that wearable EEG devices, designed in accordance with the principles of emotional ergonomics and with an enhanced focus on data-driven wellness, can achieve sleep-stage classification accuracy comparable to that of polysomnography while minimally disrupting the user's natural sleep pattern.

The research is based on a systematic review and comparative analysis of the literature, in which the authors examine methods of home-based sleep monitoring, existing approaches to the development of sleep analysis devices, and sleep biomarkers.

2. Methodology

In recent years, research on home-based sleep-monitoring technologies has converged on two principal directions: analytical reviews that examine the prospects of wearable and "nearable" devices, and empirical studies that verify their accuracy and reliability across diverse clinical and consumer settings. The first direction is represented by works that systematise the current state of sensor platforms and algorithmic solutions, whereas the second encompasses publications devoted to testing specific devices for sleep-architecture assessment and pathology detection.

Review papers concentrate on the multidisciplinary analysis of hardware and software components in home monitoring systems. Mohamed M., Mohamed N. and Kim J. G. [1] highlight recent advances in wearable EEG sensors, discussing the evolution of electrode materials, form factors and accompanying algorithms for automatic sleep-stage recognition. Kwon S., Kim H. and Yeo W. H. [2] provide a detailed examination not only of EEG devices but also of accelerometers, photoplethysmographic sensors and integrated multimodal platforms, demonstrating their potential for portable use outside the laboratory. While noting progress in power-consumption reduction and wearer comfort, the authors emphasise insufficient standardisation of validation protocols.

Cay G. et al. [4] broaden the scope by evaluating clinical standards and the integration of artificial intelligence in signal interpretation. They consider current approaches to training neural networks on large polysomnographic datasets and integrating mobile applications for user feedback. Despite rapid growth in start-ups and patents, the authors observe that only a few solutions reach clinical accreditation, slowing widespread adoption. Park K. S. and Choi S. H. [9] focus on engineering aspects of home systems, including radar-based nearable sensors and thermal cameras. Yoon H. and Choi S. H. [10] summarise progress specifically in the "nearable" category, underscoring the role of wireless transmitters embedded in furniture and the feasibility of utilising Wi-Fi signals for contact-free monitoring of movement and respiration.

The empirical body of literature primarily addresses real-world effectiveness of home monitoring systems in various patient cohorts. Kafashan M. M. et al. [3] evaluated a wireless wearable in elderly cardiac-surgery patients, demonstrating acceptable accuracy for sleep-latency and total-sleep-time estimation compared with polysomnography. Nevertheless, in individuals with arrhythmia and unstable cardiac rhythms, algorithmic errors reached 15 %, indicating a need for further model adaptation. Wood E., Westphal J. K. and Lerner I. [5] re-evaluated two popular EEG-based mobile systems for home use, comparing automatic sleep-stage classification with the laboratory gold standard.

Systematic overestimation of REM and underestimation of deep stage N3 were observed, potentially distorting clinical interpretation in patients with sleep disorders. Similar discrepancies were reported by Levendowski D. J. et al. [6], who assessed sleep biomarkers in isolated REM sleep behaviour disorder: although the algorithms were highly sensitive to rapid-eye-movement episodes, they exhibited low specificity in detecting micro-arousals.

More encouraging results were presented by Kwon S. et al. [7], who introduced new sensor form factors. Their sleep-monitoring patches showed high concordance with clinical measurements for parameters such as sleep efficiency and the apnoea–hypopnoea index while preserving comfort during prolonged wear. Tabar Y. R. et al. [8] proposed a generic ear-EEG that records cortical signals through the ear canal; preliminary trials in healthy volunteers demonstrated clarity comparable with temporal electrodes and robustness against motion artefacts.

Despite rapid progress in both directions, the literature reveals several contradictions. Novel sensors promise unprecedented comfort and independence from the laboratory, yet many systems require additional calibration and algorithmic refinement for populations with pronounced physiological deviations. Issues of validation standardisation between home and clinical “ground truth” datasets remain unresolved, and long-term monitoring aspects—such as seasonal variation, user adaptation and social influences—are insufficiently explored. Ethical and legal considerations surrounding the collection and storage of personal biometric data in home environments also receive limited attention.

3. Results and Discussion

3.1 Technological foundations of a wearable EEG system for home sleep monitoring

Modern wearable EEG devices for home sleep monitoring are based on a combination of three key components: sensor form factor and materials, signal acquisition and transmission electronics, and automatic sleep-stage classification algorithms.

Wearable electroencephalography (EEG) systems can be divided into four distinct classes according to device rigidity and form. The first class comprises rigid headbands in which the sensor module is affixed to an inflexible frame. One example is the Dreem Headband (Fig. 1), which employs five carbon-infused dry electrodes positioned at F7, F8, Fpz, O1, and O2, samples at 250 Hz, and integrates an accelerometer and pulse oximeter.

A similar approach is implemented in the Sleep Profiler X4: three frontopolar Ag/AgCl electrodes (AF7, AF8, Fpz) mounted on a substrate transmit data to the SP Portal cloud platform, while the built-in accelerometer records head movements.

A promising modification involves a rigid frontal headband with flexible silicone dry electrodes (AF5, Fp1, Fp2, AF8) equipped with a sleep-stage classifier based on the relevance vector machine (RVM) method [1].

Рисунок

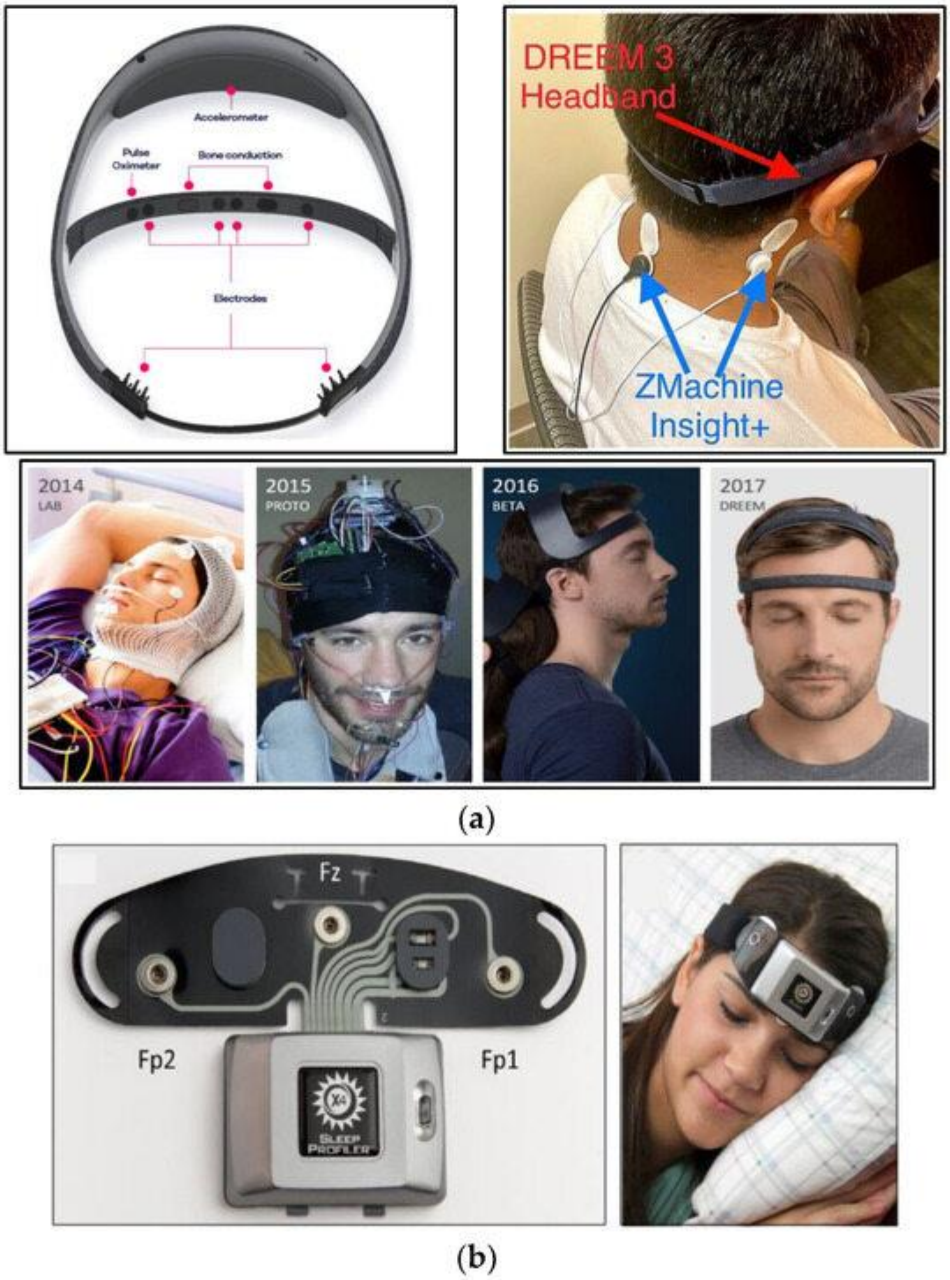

Fig.1. Rigid headbands. (a) The Dreem Headband (DH): (upper left) the configuration of sensor placements on the DH; (lower) evolution of the DH; and (upper right) simultaneous EEG signal recording with DREEM3 3 and Zmachine Insight+. (b) The Sleep Profiler (SP): (left) SP X4 with EEG electrode's locations; and (right) SP X4 in use. (c) Rigid headband with flexible EEG dry sensor: (upper left) silicon-based EEG sensor and placement of EEG channels; (lower) EEG acquisition circuit; and (upper right) wearable headband and forehead EEG sensors [1].

The second category comprises flexible headbands whose supporting strap tolerates moderate deformation. A basic design employs fabric and forms a single bipolar channel Fp1–Fp2 with wireless transmission at 2.4 GHz, after which a neural-network model performs hypnogram analysis. A more sophisticated system, the Smart Headband (Sung-Woo et al.), positions three Ag/AgCl electrodes according to the international 10–20 system (Fp1, Fp2, Fpz), integrates a low-noise ROIC, a Bluetooth interface, and a rule-based algorithm running on a microcontroller. Finally, the E-textile headband incorporates 24 printed textile electrodes (from AF8 to AF10 and beyond), digitises the signal via an ADS1299, and provides visualisation without subsequent machine analysis.

The third category consists of ultra-flexible systems in which the sensing element is implemented on thin-film or mesh substrates with minimal mechanical stiffness. trEEGrid employs pre-gelled neonatal ECG electrodes integrated into a self-adhesive mesh template on a flexible printed-circuit board, providing accuracy comparable to polysomnography ($\kappa = 0.70 \pm 0.01$). The tattoo-like system is a polyurethane film with an Ag/C pattern, coupled to a wireless module and four combined EEG/EOG/EMG electrodes, enabling seven-hour multistage monitoring. Additional variation is offered by the Soft Electrode Array matrix (Oz et al.) with an integrated processing chip, achieving 85.7 % sensitivity to REM sleep (κ = 0.688). The same family also includes a pair of ultrathin soft patches, one placed on the forehead and the other under the chin; a convolutional neural network classifies obstructive sleep apnoea events with 88.5 % accuracy [2, 7].

The classification concludes with the in-ear approach, which relocates EEG acquisition to the auditory canal. The earliest implementation, the viscoelastic earpiece, employs a fabric sensing pad mounted on a soft saline-soaked carrier and detects stages of short daytime sleep. The concept was later advanced into hardshell ear-EEG in wet and dry versions with six to twelve Ag/AgCl or dry button electrodes; automatic scoring uses a random-forest algorithm (κ ≈ 0.61–0.73). The cEEGrid system is a C-shaped Ag/AgCl array behind the auricles that users can mount in under twenty minutes; laboratory testing yields κ ≈ 0.42, and home trials confirm practical feasibility. Finally, a universal ear-EEG module with four silicone inserts of different sizes analyses 84 extracted features with a random-forest algorithm and achieves κ = 0.71 [1, 2].

All the devices listed employ a linear amplifier with a band-pass filter (~0.5–40 Hz), an ADC operating at 250–500 Hz, and wireless interfaces (Bluetooth LE or proprietary 2.4 GHz links). The main processing stages are:

Pre-processing: artefact removal (neurobiological and motion), notch filtering at 50/60 Hz, and down-sampling to 128–256 Hz.

Feature extraction: spectral density in the δ, θ, α, and β bands, relative powers, band ratios, and statistical and non-linear characteristics such as skewness, kurtosis, and Hjorth parameters [8, 9].

Table 1 presents a comparative analysis of EEG systems for sleep monitoring.

Table 1. Comparative analysis of EEG systems for sleep monitoring (compiled by the author based on the analysis: [1, 2, 7]).

Device	Form factor	Electrodes (type / material)	Channels	Fs, Hz	Classifier	κ (vs PSG)
Dreem Headband	Rigid headband	dry carbon–silicone	5 physical → 7 derived	250	LSTM + Softmax	0.75
Sleep Profiler X4	Rigid headband	Ag/AgCl (wet)	3	256	SP Auto (AASM rules)	0.68
Flexible silver-fabric	Flexible headband	silver-coated fabric (dry)	1	128	ANN	0.70
Smart Headband	Flexible headband	Ag/AgCl	3	250	decision tree	—
trEEGrid	Film–mesh patch	pre-gelled ECG	8 EEG + 2 EOG	250	manual (expert)	0.70
Tattoo-EEG	Tattoo patch	PU/Ag/C (dry)	4 EEG + 4 EOG/EMG	250	manual (AASM)	—
Soft patch (Kwon et al.)	Soft patches (forehead / chin)	nanomembrane (dry)	2 EEG + 2 EMG	250	CNN	0.76
cEEGrid	Flex-printed behind-ear	Ag/AgCl	10	500	manual / hybrid	0.42
In-ear hardshell	Ear inserts (hardshell)	dry button	12	500	Random Forest	0.73

(dry)						

*Fs — sampling rate.

Thus, wearable EEG systems combine ergonomic form factors, diverse electrode materials, and advanced algorithms (RNN, RF, CNN), delivering sleep-analysis accuracy that approaches polysomnography while preserving the comfort of home use.

3.2 Transformation of consumer perception of wellness services and the impact on the market of home sleep monitoring systems

Over the past decade, the wellness concept has undergone a fundamental shift—from an emphasis on external appearance and episodic treatments to a comprehensive approach focused on resilience, recovery, and cognitive performance. Historically, public perception equated wellness primarily with spa treatments, dieting, and gym attendance (proprietary analytical data). At present, consumers prioritize stress resilience, energy restoration, and cognitive maintenance, reflecting a transition from “beauty for beauty’s sake” to “health for life” [2]. In the coming 5–10 years, wellness is expected to evolve into an integrated system of healthcare, technology, design, and policy. Even more striking than the figures is the change in mindset: wellness is becoming proactive, data-driven, and hyper-personalized. One of the most significant advances will be the integration of biometric data—blood glucose, HRV, cortisol—into everyday decision-making. Just as smartphones disrupted communication, biometric awareness is reshaping behavior concerning stress, sleep, and nutrition.

Royal Therapy, a subsidiary of Harmonic USA LLC, leads innovation in sleep wellness by blending engineering excellence with luxurious design and uncompromising functionality. The company was founded on a straightforward yet powerful conviction: every individual deserves high-quality sleep, luxury, and enhanced well-being.

Studies indicate that 70 % of consumers actively examine the composition and safety of materials before purchasing wellness products [1, 2]. A comparable paradigm of transparency and verification has emerged in the wearables market: users demand evidence of algorithmic validity and access to raw data [5, 10]. Consequently, home sleep-monitoring technologies have become a key element in the wellness-service portfolio. New design trends encompass not only comfort and seamless sensor integration but also “emotional ergonomics,” meaning the design of devices and services that reduce stress and facilitate emotional regulation. Contemporary users expect each interaction to deliver

tangible outcomes (improved sleep quality);

methodological transparency and unrestricted access to personal data;

precise personalization of recommendations and settings.

Table 2 presents an overview of the transformation in wellness-service perception and the principal drivers of change

Table 2. Consolidated overview of the transformation in wellness-service perception and the principal drivers of change (compiled by the author based on the analysis: [1, 2]).

Aspect	≈ 2013–2015	≈ 2023–2025	Drivers of change
Primary services	Spa treatments, diets, gyms	Recovery programs, resilience, neurocognitive interventions	Findings from chronic-stress research; digital-first lifestyle
Role of sleep	Secondary; rest	Key health factor: metabolism, mental health, productivity	Association of sleep deprivation with type 2 diabetes, depression, cognitive decline
Approach to product/service	Marketing and “brands”	Data-driven: ingredient analysis, clinical verification	COVID-19 pandemic; rise in chronic diseases

selection			
User-engagement duration	One-off promotions and courses	Continuous support: apps, wearables, regular analytics	Vulnerability of healthcare systems; demand for prevention
Emotional component	Aesthetics and pleasure	Emotional ergonomics: reduced anxiety, formation of restorative habits	Pandemic, remote work, increased anxiety
Verification expectations	Brand trust	Algorithm transparency, peer-reviewed validation, user access to raw data	Surge in misleading marketing (green- and wellness-washing)

Thus, the evolution of consumer perception of wellness products and services creates favorable conditions for the widespread adoption of home sleep-monitoring systems, which require not only technical accuracy but also a high degree of trust, personalization, and emotional comfort.

3.3 Personalization and "emotional ergonomics" in the design of home sleep assessment devices

The contemporary wearer of sleep-monitoring wearables imposes both technical and emotional requirements: the device must be free of discomfort, aesthetically pleasing, adaptable to individual characteristics, and transparent in its handling of personal data. This context introduces the concept of emotional ergonomics—the design of devices that attenuate stress and cultivate a positive emotional response during everyday use.

Reliable skin contact and comfortable wear constitute the fundamental conditions for emotional comfort. The E-textile Headband demonstrates that integrating all 24 printed electrodes into a single elastic textile sheet renders both appearance and sensation during sleep imperceptible; no skin irritation is reported even after several consecutive days of use [5]. The cEEGrid with flexible Ag/AgCl electrodes positioned behind the ears can be installed within 20 minutes without technical assistance, thereby minimising anxiety among first-time users. The in-ear earpiece based on memory foam and fabric electrodes self-adjusts to the shape of the ear canal, enhancing emotional comfort and reducing motion artefacts [2, 6].

Users value clear visualisations and flexible configuration options:

- The Dreem Headband provides detailed sleep-stage reports, while its companion application allows adjustment of objectives (e.g. duration of deep sleep, sleep-onset latency) and delivers personalised recommendations [1].
- Soft patches display a real-time hypnogram on a smartphone and announce achievement of user-defined sleep-quality goals via voice feedback, thereby increasing perceived control and reducing anxiety about the accuracy of monitoring [7].
- Emotional ergonomics also encompasses respect for personal data and algorithmic integrity.
- Seventy per cent of consumers verify technological safety and scientific validity before purchase; identical expectations apply to sleep-staging algorithms, with demands for access to raw data and transparency of validation methods.
- The Smart Headband employs a rule-based decision tree that can be reviewed and modified "under the hood" through an open API, strengthening trust among advanced users [1, 3].

Elements of personalisation and emotional ergonomics in wearable EEG systems will be presented in Table 3.

Table 3. Principal elements of personalisation and emotional ergonomics in wearable EEG systems (compiled by the author based on the analysis: [1, 3, 6, 7]).

Element	**Description**	**Implementation example**
Form-factor	Adjustment to individual anatomy (head,	cEEGrid: flexible PCB tape behind the

adaptation	forehead, ear); minimisation of pressure and tension points	ears; 20-minute fit test
Interface material	Hypoallergenic, breathable fabrics and elastomers; low-profile “soft patch” construction	E-textile Headband: textile substrate with printed electrodes
Visualisation and UI/UX	Intuitive dashboard, comprehensible hypnogram, user-defined sleep-goal configuration	Dreem App: deep-sleep goal setting, voice notifications
Algorithm transparency	Access to intermediate features and results; peer-reviewed publications on sleep-staging methods	Smart Headband: rule-based decision tree in the MCU; documentation available on GitHub
Feedback and motivation	Push notifications, recommendations, gamification (leaderboards, badges) to foster regular sleep monitoring	Soft patches: real-time hypnogram, weekly deep-sleep-percentage achievements, sleep-hygiene advice
Data privacy	Local storage of raw signals, encryption prior to cloud transfer, option for complete deletion of monitoring history	Oura Ring: data stored locally until explicit export; GDPR compliance

Therefore, combining a comfortable interface, clear visualisations, transparent algorithms, and stringent privacy measures establishes a new paradigm of emotional ergonomics in wearable EEG systems, replacing a purely technical approach and focusing exclusively on user requirements.

4. Conclusion

The analysis demonstrated that wearable EEG systems have achieved sleep-stage classification accuracy comparable to polysomnography (PSG) through the combination of advanced form factors and machine-learning algorithms. Nevertheless, further adoption hinges on addressing users’ affective needs—ensuring wearing comfort, aesthetic design, an intuitive interface, and transparent data processing—within the framework of emotional ergonomics. The main prospects remain:

Multisensor integration — unifying EEG, photoplethysmography (PPG), actigraphy (ACT), and electrodermal activity (EDA) within a single device for comprehensive analysis of sleep biomarkers.

Validation standardization — developing open testing protocols and subjecting sleep-staging algorithms to public audits.

AI analytics and predictive modeling — shifting from retrospective sleep assessment to risk forecasting and personalized recommendations.

Long-term clinical studies — confirming the utility of wearable systems in preventing cognitive and metabolic disorders.

Thus, the synergy of technological innovation and a deep understanding of user motivations provides the foundation for a new generation of home sleep-monitoring systems capable of strengthening population health and enhancing quality of life across the global wellness industry.

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