Sleep Monitoring and Sleep-Aid Intervention Methods: A Review

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***Abstract*—Sleep disorders and the associated physical and mental illnesses are becoming increasingly prominent, affecting people's quality of life and work-learning efficiency. Accurate sleep monitoring and efficient sleep-aid interventions are still world challenges. In recent years, there have been significant advances in monitoring the in-and-out-of-bed state, heart rate, heart rate variability (HRV), respiratory rate, snoring event, body movement, and sleep stage, including the development and use of multimodal sensors for data acquisition and the adoption of AI techniques, such as feature extraction and pattern recognition for sleep parameter identification. Common sleep-aid methods can be categorized into two main groups: pharmacologic and nonpharmacologic. However, in the long run, it seems that the effect of a single sleep-aid method is limited, and the integration of multiple sleep-aid intervention methods is the trend. Microneedle sleep-aid techniques that integrate herbal sleep aids, acupoint acupuncture sleep aids, and transcranial current stimulation sleep aids have emerged. However, there is a lack of summarization and review of the latest research on sleep monitoring and sleep interventions in recent years, and this article hopes to point out the limitations of the current technology and suggest under-explored research paths through the investigation of the latest studies. In this article, relevant studies in the last 5–10 years have been well researched, and expertise in neuroscience, clinical medicine, biomedical engineering, computer science, mobile health, and human–computer interaction is utilized to discuss sleep monitoring and sleep-aid techniques from an interdisciplinary perspective. The principles of state-of-the-art sleep monitoring techniques, multidimensional sleep parameter recognition techniques, and physical, medical, and microneedle sleep-aid techniques are presented. In addition, the advantages and limitations of these techniques, as well as the opportunities and challenges of emerging techniques, are discussed.**

***Index Terms*—AI algorithms, hardware system, sensors, sleep-aid intervention, sleep monitoring.**

I. INTRODUCTION

ONE-THIRD of a person's life is spent sleeping, but in the current fast-paced world, quality sleep has become a luxury. According to the statistics of sleep associations in the United Kingdom, the United States, France, and Japan, the average sleep time of the French is 8.7 h, the average sleep time of the Americans is 7.5 h, the average sleep time of the British and the Japanese is 6.5 h, the average sleep time of the Americans on weekdays is less than 6 h, and the average sleep time of the Japanese on weekdays is even less [1], [2]. According to the World Health Organization, a survey of 25 916 patients attending primary care in 15 regions of 14 countries found that 27% had sleep problems [3]. The incidence of insomnia has been reported to be as high as 32%–50% in the United States, 10%–14% in the United Kingdom, 20% in Japan, and 30% in France [4]. The findings of the "China Sleep Research Report (2023)," edited by the Xilinmen Sleep Research Institute and published by the Institute of Social Research of the Chinese Academy of Social Sciences and the Zhimeng Consulting Organization, in conjunction with the China Sleep Research Society and the Sleep Center of Peking University, show that [5], [6], the sleep condition of the Chinese population is average, as evidenced by the fact that the sleep index of the Chinese population in 2022 will be 67.77 points (percentage scale). In terms of trends, the sleep indexes of Chinese residents are 71.24, 69.2, 67.5, and 64.78 h in 2018, 2019, 2020, and 2021, respectively, with 2022 marking the first rebound in the declining trend in sleep quality since 2010. The prevalence of sleep disorders ranges from 15% to 30% for domestic adults and 10% to 23% for domestic adolescents.

Currently, sleep disorders and the physical and mental illnesses caused by them are becoming increasingly prominent among Chinese residents. Sleep disorders refer to shortened sleep duration, interrupted sleep, or daytime sleepiness. Common sleep disorders include insomnia, circadian rhythm disorders, excessive sleepiness disorders (sleep apnoea,

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episodic somnolence, Restless Legs Syndrome/Periodic Limb Movement Disorder (RLS/PLMD)), and parasomnias [7], [8]. Sleep apnoea syndrome is one of the most important sleep disorders, affecting about 1 billion people worldwide and more than tripling the risk of stroke and cardiovascular mortality if left untreated [9], [10]. More than 400 million people in China suffer from sleep problems, and nearly 60% of children and adolescents are sleep-deprived. The latest research indicates that there are more than 80 kinds of sleep-related diseases, and long-term sleep deprivation will increase the risk of cardiovascular diseases, anxiety, depression, diabetes, and obesity and impair cognitive function, memory, and the immune system, thus affecting the quality of life and work-study efficiency [11]. Therefore, how to enable people to conveniently and effectively carry out sleep monitoring and quality evaluation in daily life, understand their sleep conditions, and create conditions for the discovery and treatment of related diseases is particularly important in sleep medicine, which plays an important role in the economy of the country, the people's livelihood, and the prosperity and stability of society.

Accurate sleep monitoring and efficient treatment are still worldwide problems, and well-known universities at home and abroad, such as Stanford University in the United States and Peking University in China, have in recent years listed sleep medicine as a cutting-edge cross-discipline for key development! Sleep medicine is a new cross-disciplinary discipline with strong synthesis, and the main research content includes biological mechanisms of sleep and wakefulness, circadian rhythm, pathophysiological mechanisms of various types of sleep disorders, clinical assessment, diagnosis, prevention, and treatment. For sleep monitoring and diagnosis, the most accurate and authoritative testing equipment is polysomnography (PSG), which is mainly used to detect signals of electroencephalogram (EEG), electrocardiogram (ECG), respiration, etc., to analyze and obtain the indicators of heart rate and heart rate variability (HRV), respiration rate, snoring (i.e., sleep apnoea syndrome), and sleep stages (including deep sleep, light sleep, rapid eye movement (REM) sleep (REM), wakefulness), etc. The equipment is expensive (e.g., German Somerset). Since the equipment is expensive (e.g., the PSG of the German Somno V5 costs up to RMB 450 000), only some hospitals or professional sleep monitoring organizations have this equipment, and its application is difficult to promote. The waiting period for patients to make appointments for sleep monitoring in hospitals is usually long and costly. In addition, PSG is a wearable device, and patients usually need to wear more than 50 electrodes, which is very troublesome and time-consuming. The multiple electrodes connecting to the device will have a certain impact on their sleep, and unconscious sleep movements during the night may also lead to the detachment of some electrodes, which will affect the measurement results. It can be seen that expensive, uncomfortable, inconvenient, and other problems are the main reasons why PSG cannot be popularized and applied to all people. Therefore, the realization of convenient sleep monitoring and quality analysis at home is of great practical significance for the practical improvement of the sleep health of the nation (especially the youth and the elderly) and also for the promotion of the national economy and social development. Sleep monitoring and sleep quality analysis can be used not only for the diagnosis of sleep disorders but also for the evaluation of the effectiveness of sleep aids, so that doctors can adjust their interventions according to the results of this feedback. Common sleep-aid interventions can be divided into two categories: pharmacological and nonpharmacological interventions. Pharmacological sleep-aid interventions mainly include Western medicine and traditional chinese medicine (TCM). Nonpharmacological sleep-aid interventions mainly include two major categories: psychological intervention and physical intervention.

However, there is a lack of summarization and review of the latest research on sleep monitoring and sleep interventions in recent years. In this article, the research and review are centered on two major issues in the field of sleep medicine: sleep monitoring and sleep intervention, which can form a closed loop: sleep monitoring provides a scientific basis for intervention, and the effect of intervention is optimized through the feedback of monitoring, forming a dynamic cycle. This article hopes to point out the limitations of the current technology and suggest under-explored research paths through the investigation of the latest studies. The contributions of this article include.

1) The relevant methods concerning sleep monitoring and sleep aid interventions during the last 5–10 years are comprehensively introduced; for sleep monitoring, the principles of sleep monitoring and multidimensional sleep parameter recognition techniques are highlighted, and for sleep aid methods, physical, medical and microneedle sleep aid techniques are highlighted.
2) The advantages and disadvantages of the relevant methods are discussed and compared.
3) The not fully researched directions of the current research status are explored, and the future technological trends are predicted.

II. SLEEP MONITORING

A. *Principles of Sleep Monitoring*

Sleep quality is related to age, cardiovascular, neurological, and mental health, reflecting the organization of the autonomic nervous system (ANS) and the homeostatic state of circadian rhythms [12]. The ANS consists of the sympathetic and parasympathetic nervous systems, which are usually dominated by the sympathetic nerves during waking or stressful states and the parasympathetic nerves during sleep or relaxation. Sleep stages mainly consist of REM and non-REM (NREM) stages, and (NREM) stages include wakefulness, light sleep, and deep sleep stages. The main types of sleep apnoea are obstructive sleep apnoea (obstructive sleep apnea (OSA)), central sleep apnoea, and compound sleep apnoea, of which OSA is the most common and can be treated or suppressed by proper sleep posture [13]. Sleeping postures usually include supine, left side, right side, and prone. During sleep, lying on the back tends to cause a partial or complete collapse of the upper airway, thus leading to airway obstruction

TABLE I
NONCONTACT MONITORING METHODS

Sensor	HR&HRV	Breathing Rate	Snore	Sleep Posture	Sleep Stage
Camera		√		√	
RF Sensors	√	√			
WIFI		√		√	
microphone			√		

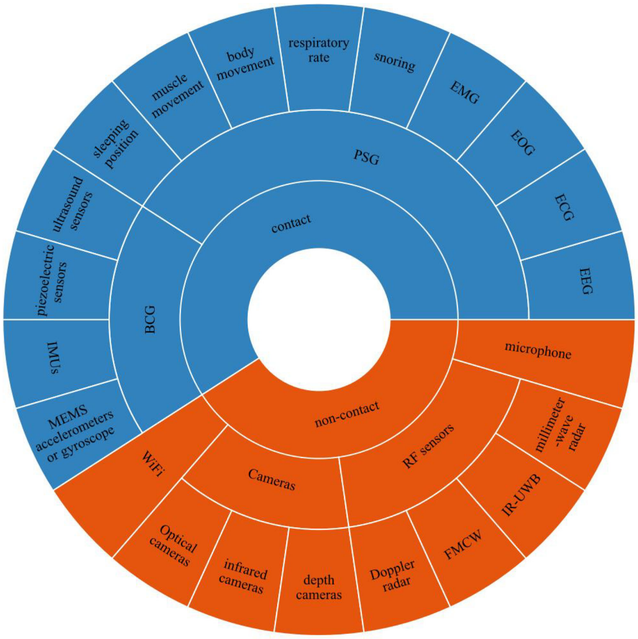

Fig. 1. Sleep monitoring methods.

and snoring, while lying prone increases the pressure on the heart and lungs, thus leading to poor sleep quality, both of which can be alleviated and suppressed by lying on the side. The apnea-hypopnea index (AHI), defined as the total number of complete and partial upper airway obstructions per hour, is used to characterize the severity of OSA. Severity was categorized into 4 categories based on AHI values: normal (AHI < 5); mild ($5 \leq$ AHI < 15); moderate ($15 \leq$ AHI $<$ 30); and severe (AHI ≥ 30). In mild snoring, episodic snoring is most common, whereas in moderate or severe snoring, persistent snoring is likely to occur. Autonomic changes and sleep-disordered breathing (SDB) in different sleep stages can be characterized by HRV, in addition to stress, fatigue, and emotions [14], [15], [16], [17].

Currently, the gold standard technique for assessing sleep quality is PSG, which is a combination of electroencephalography (EEG), electrocardiography (ECG), electrooculography (electrooculogram (EOG)), and electromyography (electromyogram (EMG)) [18], [19]. EEG signals can be classified into five categories according to frequency bands: δ-waves (0.5–4 Hz), θ-waves (4–8 Hz), α-waves (8–14 Hz), β-waves (14–30 Hz), and γ-waves (30–64 Hz) [20], [21]. δ waves are generally seen in states of deep sleep, extreme fatigue, deep anesthesia, and hypoxia, and are highly visible in the frontal and occipital lobes. θ waves are generally seen in states of deep sleep, drowsiness, and depression, indicating central nervous system (CNS) suppression, which is highly visible in the frontal and parietal lobes. α waves are often seen in states of light sleep and relaxation, and are highly visible in the frontal, occipital, and parietal lobes. β waves are often seen in eye-opening, tense, excited, or thinking states, and are evident in the frontal and parietal lobes. γ waves are often seen in high-pressure, high-stimulus, and high-anxiety states, and are evident in the frontal and parietal lobes. Based on the changes in the five brain waves, combined with the heart rate, HRV, respiratory rate, snoring event, body movement, muscle movement, and sleeping posture detected by PSG, indicators, such as sleep stage and sleep quality can be analyzed and obtained. Given that PSG bioelectrical monitoring systems are uncomfortable to wear and their sleep monitoring is time-consuming and expensive, it is difficult to promote their use. Given the importance of sleep monitoring, more and more research organizations have invested a lot of research and proposed nonbioelectrical monitoring methods, including contact and noncontact monitoring methods.

For noncontact monitoring methods, cameras, RF sensors, WiFi, or microphone solutions are often used, and the sleep parameters that they could capture are shown in Table I, respectively. Sensors, sleep parameters, and accuracy used in related studies are demonstrated in Table II. Optical cameras, infrared cameras, and depth cameras can be used to detect respiration rate and sleep posture, but they are unable to monitor heart rate and sleep stages and can raise serious privacy concerns [22], [23], [24]. In addition, Doppler radar, frequency-modulated continuous wave (FMCW), impulse radio ultrawideband (IR-UWB), and millimeter-wave radar sensors can be used to detect heart rate, HRV, and respiratory rate, but they are very expensive and the results are susceptible to interference from the presence of multiple people in the same space [25], [26], [27], [28], [29]. While the WiFi transmitter and receiver can be used to detect respiration rate and sleep posture during sleep [30], [31], they are unable to monitor heart rate and HRV, making it difficult to accurately identify sleep stages. Microphones are commonly used to monitor snoring events and can be integrated into smartphones or pillows because of their small size and low cost [32], [33], however, monitoring by a single sensor can be easily interfered with by noise in the environment, and microphones are unable to detect vital signs and sleep states. Given the shortcomings of noncontact detection methods, most current sleep monitoring methods utilize contact monitoring methods, where contact monitoring methods can be further categorized into wearable and nonwearable monitoring methods, as shown in Fig. 1.

For wearable monitoring methods, ultrasound sensors, piezoelectric sensors, micro-electro-mechanical systems (MEMSs) inertial measurement units (IMUs), MEMS accelerometers, or MEMS gyroscope solutions are often used. Ultrasound sensors or piezoelectric sensors can be used to detect OSA events [34], [35], but users wearing sensor probes around their necks can be uncomfortable, and rolling over or sweating may also affect detection accuracy. Sleep quality is related to sleep movements, hence, smart bracelets, wristbands, or chest bands consisting of MEMS

TABLE II
SENSORS, SLEEP PARAMETERS, AND ACCURACIES OF THE RELATED STUDIES

Reference	Sensor	Sleep Parameter	Results
Deng et al. [22]	infrared camera	breathing and posture analysis	accuracy is 96% in recognizing abnormal breathing
Wang et al. [23]	NIR videos	sleep posture	accuracy: 80%
Jakkaew et al. [24]	thermal camera	breath	RR was obtaining an RMSE of 1.82±0.75 bpm
Wang, et al. [25]	commercial millimeter-wave (mmWave) radio	HRV	accuracy: 96.16%
Hur et al. [26]	multi-input multi-output (MIMO) frequency-modulated continuous wave (FMCW) radar	HRV	average absolute error percentage of 1.03%
Baboli et al. [28]	quadrature microwave Doppler radar	Actigraphy and sleep apnea detection	an overall sensitivity of 86%, the specificity of 91% and accuracy of 92%.
Ahmed et al. [29]	IR-UWB radar	HRV	the LF/HF ratio measured using IR-UWB radar was highly reliable, accurate and convenient compared to that measured using ECG
Gu et al. [30]	WIFI	stationary/active states	achieves 95.65% detection accuracy
Yu et al. [31]	WIFI	respiration and body movement	achieves an accuracy of 81.8%
Markandeya et al. [32]	smart phone	Using sleep related respiratory sound (SRS) to predict overnight airway obstruction severity	SRS based: a median of absolute error of 6.75 cmH2O (±0.59, r = 0.83(±0.03)). PSG + SRS: 6.37cmH2O (±1.02, r = 0.85(±0.04))
Weng et al. [34]	ultrasound	tongue base thickness (TBT) during obstructive sleep apnea (OSA)	TBT increased significantly during snoring, hypopnea and apnea events during natural sleep in patients with OSA
Kuo et al. [36]	MEMS, a three-axis accelerometer	sleep efficiency (SE)	For wake-sleep staging, the average accuracy, sensitivity, specificity, and kappa coefficient were 92.16%, 95.02%, 71.30%, and 0.64, respectively. For the assessment of SE, the accuracy of classifying good or poor SE reached 91.53%. The mean biases of SE, sleep onset time, wake after sleep onset, and total sleep time were -0.95%, 0.74 min, 2.84 min, and -4.3 min, respectively.
Pigeon et al. [37]	MEMS, accelerometer	sleep-wake scoring	Percent agreement with PSG-scored wake and sleep was 91.3% for MC (kappa = 0.67) and 87.7% for AW (kappa = 0.50). Positive predictive values for sleep epochs were 94.4% and 90.8% for MC and AW, respectively, and 74.5% and 65.6% for wake.(MC: new device, AW: new device)
Boe et al. [38]	multimodal sensor	hand acceleration, electrocardiography, and distal skin temperature	detecting wake and sleep with a recall of 74.4% and 90.0%, respectively, as well as wake, non-REM, and REM with recall of 73.3%, 59.0%, and 56.0%, respectively
Tadi et al. [43]	gyroscope	cardiac time interval measurements such as systolic time intervals (STI) and diastolic time intervals (DTI).	Linear correlation of r 2 = 0.88
D'Mello et al. [45]	MEMS gyroscope and accelerometer,	heart rate	normal (averaged) heart rates: r2=0.9783 instantaneous (beat identification) heart rates: r2=0.9982
Milena et al. [46]	accelerometer and gyroscope	HRV	using the gyroscope signal in the lying posture allows accurate results in estimating interbeat intervals (IBIs) HRV parameters are not statistically significantly different from those extracted from reference ECG
Wang et al. [47]	piezoelectric ceramic sensor	heart-rate	high heart-rate detection accuracy 99.18% was achieved
Matar et al. [48]	pressure sensors	breathing rate (BR)	a high inter-rater agreement, an average maximum difference of 1.93 Breaths Per Minute (BrPM), a confidence interval of 95%, along with a strong linear relationship of 95.8% on average compared with respiratory belts
Peng et al. [49]	micro pressure sensor	heart rate variability, heart rate, body moving number, respiratory rate, sleep apnea time, snoring time and body moving time	/
Chao et al. [50]	air pressure sensor	sleep postures	The F1-score of the CNN model determined by the ablation experiment is 98.1%
Perez-Macias wt al. [53]	electromechanical film transducer	snore	the sensitivity, and the positive predictive value of the developed method to reveal snoring from the Emfit signal were 82.81% and 86.29%, respectively
Adil et al. [54]	optical blood flowmeter instrumentation	blood flow rate of organism	accurate to measure cerebral blood for monitoring of sleep
Li et al. [55]	two single mode fibers (SMFs) and a multimode fiber (MMF) with a grid structure	activity rhythm, sleeping state and sleeping respiratory rates (SRR)	it can continuously monitor the sleeping activities and respiration of the dog, includes activity rhythm, sleeping state and sleeping respiratory rates (SRR)
Chen wt al. [56]	even-core fiber interferometer (SCFI) sensor,	heart rate (HR) and respiration rate (RR)	The standard deviation (SD) of HR and RR between our proposed sensor and commercial physiologic device are 1.17 bpm and 2.16 rpm, respectively.
Kim et al. [57]	passive infrared (PIR) motion sensors	sleep-wake conditions	multilayer feed-forward neural network achieved 96.61% in detecting sensitivity, specificity is 91.81% and AUC performance is 94.21%.
Li et al. [58]	vibration sensor	heartbeat rate (HR) and respiratory rate (RR), body movements and sleep postures	HR data smoother than Apple Watch, Sleep Posture Detection: Recall: 0.86; Precision: 0.853; Accuracy: 0.924.

IMUs, accelerometers, or gyroscopes can be used to collect sleeping postures and sleep data [36], [37], [38]. However, it is uncomfortable for the user to wear these devices all night long, and in the case of bracelets and wristbands, it is difficult to accurately recognize the different sleep stages based on the movement of the hand alone. For nonbioelectrical monitoring methods, cardiac mechanics-based sleep monitoring methods are often used today, including ballistocardiograph (BCG), seismocardiography (SCG), and gyrocardiography (GCG). The BCG measures the whole-body recoil or ballistic force as blood is ejected from the aorta into the vascular tree [39], [40], the SCG measures the 3-D linear acceleration induced by cardiac vibration in the chest [41], [42], and the GCG measures the 3-D angular rate induced by cardiac vibration using a gyroscope mounted on the chest [43], [44]. SCG and GCG generally measure localized vibration in the chest through inertial sensors worn on the chest [45], [46], and wearing the products often leads to discomfort for the user, whereas BCG is a nonwearable, contact-monitoring method, which is widely adopted as it generally does not require any products to be worn to measure the overall vibration of the human body in order to determine sleep quality.

For BCG nonwearable monitoring methods, mechanical vibrations caused by the opening and closing of heart valves can be captured by piezoelectric ceramic sensors, pressure sensors, piezoelectric thin-film sensors, fiber-optic strain sensors, MEMS IMUs, accelerometers, or gyroscopes, which can be integrated into chairs, pillows, bedsheets, mattresses, or beds and which have unobtrusive designs that are more comfortable to use. Piezoelectric ceramic sensors mounted in the cavity of memory foam pillows can also be used for sleep monitoring [47], but the cost of the pillows is also high, and the circuit boards and batteries mounted in the pillows dissipate heat poorly and with a high-risk factor. Pressure sensor arrays embedded in sheets, mattresses, or beds can monitor respiratory rate and sleep posture [48], [49], [50] with high detection accuracy, but it is difficult to accurately measure heart rate and HRV, and the product is both complex and expensive. Flexible materials, such as polyvinylidene fluoride film (PVDF) or electromechanical film (EMF) are usually embedded in mattresses or monitoring belts for monitoring heart rate, HRV, respiratory rate, body movements, and sleep stages [51], [52], [53]. Their detection sensitivities are very high, but their costs are also high. Similarly, fiber optic interferometry and laser blood flowmeters embedded in mattresses or monitoring tapes can be used for sleep monitoring [54], [55], [56], and despite the improved accuracy, they are much more costly and complex to manufacture than either of their predecessors. In order to reduce the cost, MEMS IMUs, accelerometers, or gyroscopes have been gradually used for BCG sleep monitoring in recent years, and they are also usually embedded in mattresses or monitoring belts [57], [58], which have a high accuracy in detecting heart rate, respiratory rate, and body movements, but the accuracy in detecting HRV, snoring, and sleeping posture has not been reported.

In summary, it is usually difficult for a single sensor to simultaneously detect parameters, such as in-and-out-of-bed state, heart rate, HRV, respiratory rate, snoring event, body movement, and sleep stage, which also tends to lead to misclassification. Therefore, in order to improve accuracy, multisensor fusion (e.g., fusion of IMUs and flexible pressure sensors [59], [60]) for sleep monitoring is a future trend.

B. Multidimensional Sleep Parameter Recognition Techniques

The process of recognizing parameters, such as in-and-out-of-bed state, heart rate, HRV, respiratory rate, snoring event, body movements, and sleep stages consists of two main parts, i.e., feature extraction and pattern recognition, as shown in Fig. 2. There have been comprehensive analyzes and discussions of artificial intelligence algorithms for sleep staging [61], but not about pattern recognition of sleep parameters.

In terms of feature extraction, since the vibration or sound signals detected by the sensors are usually very weak, they need to be filtered and amplified during the data acquisition process, which is generally carried out by using infinite impulse response (IIR) filters for high-pass, low-pass, band-pass, or band-stop filtering, and then the filtered data are subjected to feature extraction. There are more methods for feature extraction, and for vibration signals, time-frequency analysis, statistical analysis (e.g., mean, variance, standard deviation, maximum, minimum, median, and plurality), and principal component analysis (PCA) methods are usually used for feature extraction. For acoustic signals, feature extraction is usually performed using over-zero rate, energy [62], energy entropy, spectral center of mass, spectral bandwidth, spectral entropy, spectral flux, empirical mode decomposition, mel-frequency cepstral coefficients (MFCC) [63], [64], discrete wavelet transform [65], denoising autoencoder technique, gamma pitch frequency cepstrum coefficients, and improved MFCC [66], [67] methods. Since sensor fusion is used for detection, the feature extraction method also needs to incorporate multiple feature extraction algorithms to improve the accuracy of subsequent pattern recognition.

For pattern recognition, take snoring recognition as an example, considering the variety of sound signals in life, including speaking, coughing, snoring, popping, wheezing, asthma, music, animal calls, environmental noise, etc. [68], therefore, in order to accurately distinguish snoring from other sounds, AI-based pattern recognition is essential. Regarding the intelligent recognition of snoring, various methods have been reported at home and abroad in recent years, such as support vector machine (SVM) [69], random forest [70], ResNet, ResNet-18, ResNet-50, long–short-term memory (LSTM), multibranch deep learning network, and integrated deep learning network [71]. In addition, some combined models, such as convolutional neural networks (CNNs) fused with recurrent neural networks (RNNs) [72] and deep neural networks (DNNs) fused with LSTM [73], have also been reported. All of these intelligent recognition-based methods achieve about 95% detection accuracy, but the implementation of these algorithms is very complex and difficult to implement in a local microprogrammed control unit (MCU), which limits the promotion of real-time snoring detection for home applications. Even if these algorithms can be implemented on cloud servers, remote data transfer and processing are very time-consuming, costly, and unreliable, making Internet of Things (IoT) edge computing imperative. Although some lightweight convolutional networks [74], [75] have been reported, their architectures are still complex and difficult to implement at the edge. Although

Fig. 2. Sleep parameter recognition techniques.

FPGA chips can be used to implement AI (e.g., CNN-LSTM) processors, their cost and power consumption are very high and therefore also unsuitable for low-cost IoT systems [76]. In addition to machine learning, similarity analysis can also be applied to sound analysis, which is simple to implement but does not have high recognition accuracy [77], [78]. The combination of machine learning and algorithms, such as similarity analysis is the trend, considering factors such as cost and complexity of IoT edge computing. In addition, to ensure data security and legitimacy, data analytics algorithms need to consider incorporating blockchain technique to protect user privacy [79].

Similarly, for sleep stage and posture recognition, artificial intelligence-based pattern recognition methods are commonly used. There are two main types of classifiers available, namely, image signal-based classifiers and vital signs-based classifiers. For image signal-based classifiers, image data obtained from optical, thermal, depth, or pressure sensing arrays is fed into the classifier to recognize sleep stages and postures. SVM, ResNet, CNN, and hidden Markov model (HMM) were used for the recognition, and the detection accuracy ranged from 83.0% to 99.8% [80], [81], [82]. Image-based classifiers have high detection accuracy, especially for deep learning models, but are expensive to implement and difficult to implement on edge processors. For the vital sign-based classifier, the vital sign data collected by devices, such as EEG, ECG, BCG, SCG, or GCG is fed into the classifier to recognize the sleep stages and postures. After preprocessing the vital sign signals, *k*-nearest neighbor (KNN), plain Bayesian (NB), *K*-mean clustering, decision tree (DT), swin transformer (ST), SVM, and CNN are used for the recognition, with detection accuracies ranging between 80.8% and 99.67% [83], [84], [85], [86], [87], [88]. In the latest research advances, sleep cycle classifiers based on EEG or PSG signals use

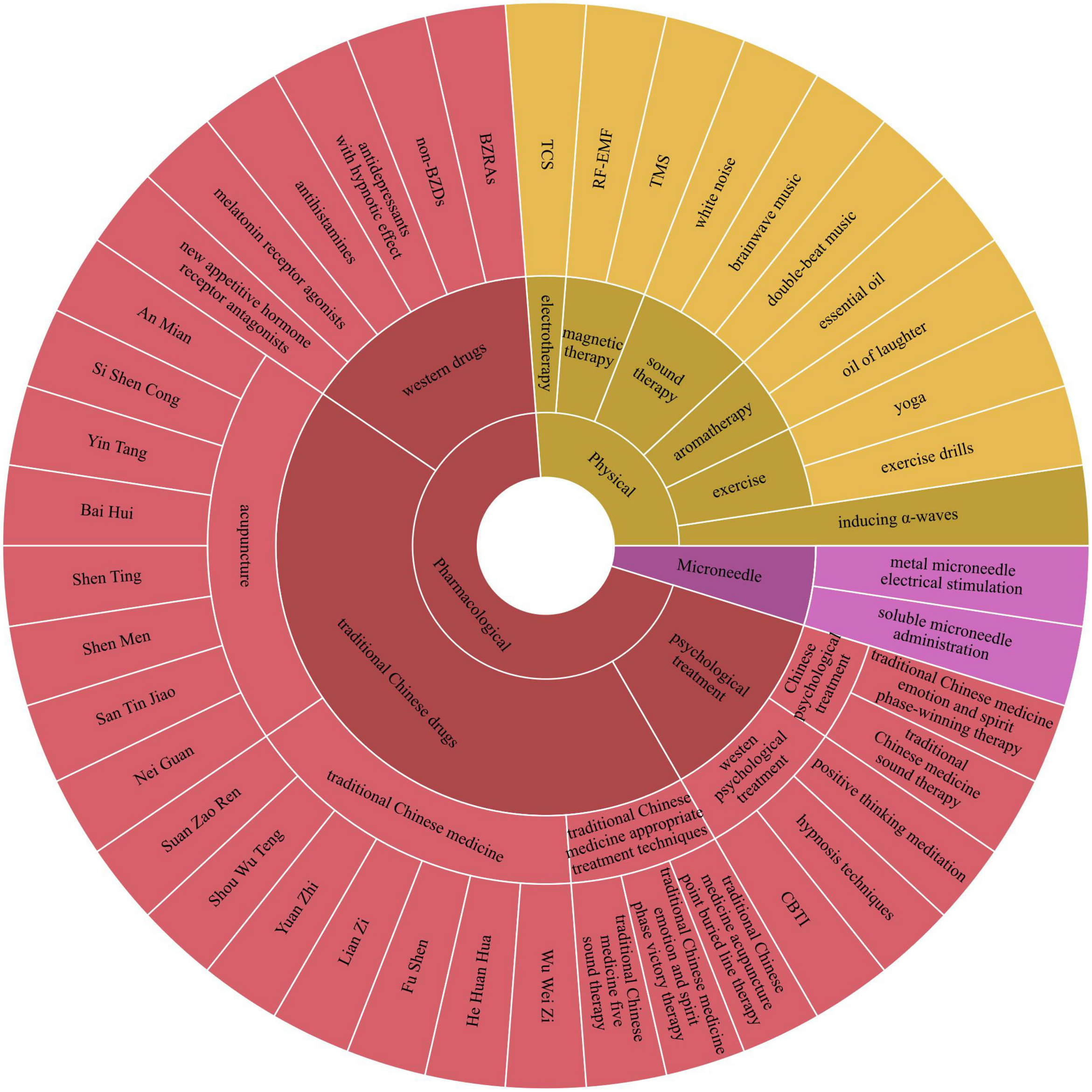

Fig. 3. Sleep-aid intervention methods.

Mamba-based deep learning models, but it is not yet conclusive whether these models can be used on edge-embedded devices [89], [90], [91]. Vital sign-based classifiers have higher detection accuracy, even with simple machine learning models.

Therefore, in order to implement sleep stage and posture recognition in low-cost edge processors, the trend is to use minimalist machine learning models or ultralightweight convolutional models to analyze vital sign signals.

III. SLEEP-AID INTERVENTION

Sleep-aid techniques can be categorized into physical sleep-aid techniques, medical sleep-aid techniques, and microneedle sleep-aid techniques, as shown in Fig. 3, and details of these three techniques are described, respectively, in this section.

A. *Physical Sleep-Aid Techniques*

Brain waves and HRV are commonly used to assess sleep or assisted sleep states. Brain waves include δ, θ, α, and β waves, which indicate the different characteristics of sleep stages [20], [92], [93]. θ-waves (4–8 Hz) and α-waves (8–14 Hz) are usually present in the first stage of sleep; in the second stage, the amplitude of the EEG signal increases and θ-waves are more prominent; in the third stage, θ- and δ-waves (0.5–4 Hz) are more pronounced; β-waves (14–30 Hz) are more predominant in the REM and wakefulness phases. In general, sleep and the effectiveness of sleep aids can be determined based on the energy of alpha waves. The phenomenon of attenuation and disappearance of alpha waves is considered to be a universal pattern that has been shown to occur more readily at higher levels of sleep, signaling entry into sleep [94]. It can be detected during eye closure and used as an indicator of the current level of drowsiness, such as sleep onset or relaxed wakefulness [95]. In addition, the alpha frequency of insomniacs bounced back to wakefulness levels, whereas that of healthy individuals remained at short-wakefulness levels after sleep onset. Reduced presleep alpha wave variability may indicate dysfunction of alpha wave generation mechanisms

TABLE III
SLEEP-AID INTERVENTION METHODS AND EFFECTS

Reference	Intervention method	Effect
Koomhin et al. [103]	michelia oil	reduce the alertness level observed by beta wave decrease and fast alpha wave activity increase.
Kusumandari et al. [110]	sundanese music and aromatherapy bio-composite	EEG signal frequency with music stimuli is higher than aromatherapy stimuli statistically
Lee et al. [100]	binaural beat	induce the brain signals required for sleep
Gao et al. [101]	slow-wave sleep (SWS) brain-wave music	positive effect on sleep quality
Dubey et al. [112]	432 Hz music	significant calming effect as reflected by increased alpha activities without any significant effect upon the sleep latency in the daytime naps
Danker-Hopfe et al. [113]	radiofrequency electromagnetic fields	a significant reduction in arousals, a shorter latency to sleep stage N3, and a shorter self-reported time awake after sleep
Dorokhov et al. [114]	weak extremely low frequency electromagnetic field	did not reveal any sleep-disturbing effects, total duration of sleep increased
Andrianome et al. [115]	electromagnetic fields	no statistical difference
Pengo et al. [122]	transcutaneous electrical stimulation	improves upper airway obstruction and is well tolerated.
Wu et al. [123]	sedative-hypnotic drug	insomnia and sedative-hypnotic use were independently associated with increased frailty
Peter et al. [127]	non-prescribed sedatives/hypnotics	co-occurrence between NMUSH and distinct BAs among young adults

in insomnia [21]. If the power spectral density of α-waves gradually increases at the onset of sleep, it means that the sleep stage is entering light sleep. Therefore, inducing the production of α-waves is an effective sleep aid.

In terms of cardiac evaluation, HRV is often used to understand autonomic changes during different sleep stages. It is also used to understand the effects of SDB and insomnia on sleep and daytime [14], [96]. HRV can also be used to monitor the effects of continuous positive airway pressure ventilation (CPAP) and to assess sleep quality [83]. In addition, slow-wave sleep (SWS) plays an important role in neurophysiological phenomena and can also be detected and assessed by HRV [17], [97]. In conclusion, HRV is suitable for assessing the feasibility of assisted sleep methods.

Currently, sleep aids are receiving more and more attention, and corresponding research results are gradually being reported as shown in Table III. Among them, exercise, aromatherapy, sound therapy, magnetic therapy, and electrotherapy are popular. Among them, exercise mainly includes exercise drills, yoga [98], [99], sound mainly includes double-beat music, brainwave music, white noise [100], [101], [102], and aroma includes oil of laughter, essential oil [103], [104], which have a certain effect of sleep aid but mainly have an auxiliary effect. Common medical-grade physical interventions mainly include transcranial magnetic stimulation (TMS), transcranial electrical stimulation (TES), and acupuncture [105], [106], [107], which regulate wakefulness and sleep through the cortical-hypothalamic top-down sleep-wakefulness regulatory pathway and are more effective in aiding sleep. TMS devices are very expensive and generally can only be used in hospitals. Comparatively speaking, transcranial electrical stimulators are less costly and more suitable for home use as a sleep aid. It has been found that both high-frequency (> 50 Hz) and low-frequency (<10 Hz) current stimulation can promote sleep [108], [109], but there is no specific frequency that should be used for sleep regulation. Furthermore, the electrodes of the transcranial electrical stimulators are mostly flat, with different contact impedances for different skins, and larger impedances will affect the effect of electrical stimulation. Acupuncture requires a high degree of skill, relies on a wealth of experience to find the right acupuncture points, and generally requires a specialized physician to complete.

Michelia essential oil reduces the level of alertness observed through β wave decreases and increases in rapid α wave activity [103], and it has a calming effect on human brain responses suitable for sleep induction. However, musical stimulation is statistically more effective as a sleep aid than aromatherapy stimulation [110]. Music can affect brain waves, such as alpha waves, and it could stimulate strong emotions [111]. When we hear two pitched sound beats in each ear at the same time, a binaural beat is created that induces brain signals at a specific desired frequency. Auditory stimulation induces brain signals needed for sleep while keeping the user mentally comfortable [100]. In addition, SWS brainwave music may have a positive effect on sleep quality, whereas REM brainwave music or white or pink noise may not accomplish this [101]. Music at 432 Hz had some significant sedative effects, as evidenced by increased alpha wave activity without any effect on sleep latency for daytime napping [112].

The effects of radiofrequency electromagnetic fields (RF-EMF) on sleep are heterogeneous. Observed changes suggest a sleep-promoting effect of RF-EMF exposure [113]. However, the limitation is that these results cannot be generalized to men and women of all ages. Exposure to very slow EMFs does not show any sleep-disrupting effect; on the contrary, it promotes sleep because the total duration of sleep is increased [114]. Melatonin is a circadian hormone that plays an important role in the sleep process. However, melatonin secretion decreases with age, which causes more people to suffer from insomnia. Fortunately, melatonin secretion and sleep architecture may be regulated by EMF [115], [116]. It is claimed that an electromagnetic field equivalent to the geomagnetic field can help one achieve restful and deep sleep; however, there is no supporting experimental data [117]. Similarly, the microwave scattering method at a certain frequency can be used for both noncontact sleep stage detection and sleep disorder treatment [118]. However, prolonged direct exposure to RF-EMF is not good, as it can lead to depression, stress, anxiety, and poor sleep quality [119]. For the diurnal current input case, when electromagnetic induction and its noise are considered, wake-up time is delayed and sleep time is advanced [120]. In addition, sleep duration is slightly prolonged by increasing noise intensity. The SWS stage can be recognized by fusing temperature, heart rate, and body motion sensors and increased with electrical stimulation [121]. Transcutaneous electrical stimulation therapy is effective in some patients with OSA, but it has not been shown whether it aids sleep [122].

In this section, the current state of research on physical sleep aid methods, including exercise therapy, aromatherapy, sound therapy, magnetic therapy, and electrotherapy, is systematically reviewed, and their effectiveness, mechanisms, and applicability are critically evaluated. Overall, physical sleep aids have emerged as important interventions for improving sleep due to their nondrug dependence, low invasiveness and favorable user acceptance, but significant differences exist between methods in terms of strength of scientific evidence, individual difference response and long-term effects.

B. Pharmacological Sleep-Aid Techniques

When it comes to professional pharmacological sleep aids, Western medicine, TCM, psychological treatment, and Chinese psychological treatment are the most commonly used technical solutions. Despite the combination of other nonpharmacological therapies in the technological program of Western medicine for the treatment of insomnia, the key techniques are still dominated by psychotropic medicine [123]. Western medicine mainly include benzodiazepine receptor agonists (BZRAs) and nonbenzodiazepine hypnotic medicine (non-BZDs), antidepressants with a hypnotic effect, antihistamines, melatonin receptor agonists, new appetitive hormone receptor antagonists, and so on [124], [125], [126]. Western medicine is very effective in treating insomnia in the short term, but its main problem is that with the long-term use of sedative-hypnotic medicine, side effects are very pronounced [127]. First, it is easy to lead to medicine dependence, withdrawal of insomnia symptoms that recur or are worse than before, and emotional and psychological problems; second, it is easy to cause drug resistance and poor adherence, from a single drug treatment upgraded to a combination of several medicine and even forced the development of new medicine, increasing treatment costs. At present, Western medicine have no effective solution to this.

TCM is more effective in aiding sleep because it systematically regulates the balance of yin and yang in insomnia patients from the root. Commonly used Chinese herbs for sleep aids include ziziphi spinosae semen (Suan Zao Ren), polygonum multiflorum (Shou Wu Teng), polygala tenuifolia (Yuan Zhi), nelumbo nucifera (Lian Zi), wolfiporia cocos (Fu Shen), schisandra chinensis (Wu Wei Zi), etc. [128]. Studies have shown that ziziphi spinosae semen and polygalae radix can alleviate insomnia in mice by attenuating pathological changes in the brain and restoring abnormal levels of neurotransmitters, endocrine hormones, and cytokines [129]. In terms of safety, all herbal therapies showed nonsignificant or lower differences in the risk of gastrointestinal reactions and dizziness events compared to Western drugs or placebo [130]. Although herbal medicines have fewer side effects, boiling them is a complicated process, and drinking them is an even more painful experience.

The technical solutions for the treatment of insomnia in Chinese medicine, at present, clinically, are mainly to take acupuncture or TCM modality [131], [132], with some TCM appropriate treatment techniques, such as TCM five sound therapy, TCM emotion and spirit phase victory therapy, and TCM acupuncture point buried line therapy. The short-term therapeutic effect of TCM is inferior to that of Western medicine, but its treatment emphasizes the systematic regulation of the balance of yin and yang, so the long-term therapeutic effect is relatively good and the side effects are low. However, its main problem is that it is effective for patients with simple or transient insomnia, but for the majority of patients with psychosomatic or prolonged insomnia, it is still ineffective and prone to relapse, etc. The main problem is that it is not effective for the majority of patients with insomnia.

The key techniques of the technical program of psychological treatment are cognitive behavioral therapy for insomnia (CBTI), hypnosis techniques, and positive thinking meditation [133], [134]. Cognitive-behavioral therapy is now recognized as the treatment of choice for insomnia disorders [135], [136], [137], and together with positive thinking, meditation can effectively improve the sleep quality of insomnia patients. Although its sleep-aiding effect is also good, it is mainly used for insomnia caused by psychological problems, and the CBTI treatment process requires long-term follow-up treatment by specialized doctors as well as the active participation of patients, making it difficult to promote.

The technical program of TCM psychological treatment is mainly rooted in TCM and was proposed in the 1980s. Due to the integration of TCM theory and psychology theory, its sleep-aiding effect is more obvious [138]. However, its main problem is that TCM psychologists mostly focus on the theoretical study of TCM psychology but less on clinical research. Most scholars of TCM psychology are confined to acupuncture and medicine, and at present, there are fewer applications of TCM sound therapy and TCM emotion and spirit phase-winning therapy to the clinical treatment of insomnia, which are similar to modern CBTI but lack the deep theoretical organization of the cognitive system, and the clinical efficacy is often unsatisfactory.

Therefore, it is necessary to develop modernized and technologized TCM psychotherapy, which is rooted in Chinese culture and TCM, picks up the nutrients of modern psychology and modern psychological techniques, fits in with Chinese people's cultural heritage, thinking structure, cognitive style, and disease characteristics, and combines with many years of academic research and clinical observation to put forward new Chinese local sleep control techniques that are suitable for the characteristics of the largest number of Chinese people who suffer from insomnia. In this regard, Wang Weidong, Vice President of Guang'anmen Hospital of the China Academy of TCM and Professor at Beijing University of TCM, put forward a set of systematic low-impedance ideas for the introduction of sleep regulation techniques called TIPI, which is based on the Three Divine Principles of TCM and supplemented by TCM needles and medicines [139], [140], [141]. The techniques invoke the structure of the TCM discipline system, both the nonpharmacological therapy of TCM to cure the root cause and the TCM acupuncture and pharmacological therapy to save the waste, which can effectively avoid the shortcomings of Western drug therapy, psychology, CBTI therapy, and other techniques.

Usually, the effect of a single sleep aid is limited, so the integration of multiple sleep-aid methods is the development trend [142]. The above analysis shows that TCM is a better pharmacological sleep aid, acupuncture and transcranial current stimulation are better nonpharmacological sleep aids, and the combination of the three will achieve a better sleep-aid effect; however, there are some shortcomings of all three at present. In response to these shortcomings, in recent years, Peking University has proposed dissolvable microneedle drug delivery techniques and metal microneedle brain-computer interface electrodes [143], [144], which can simultaneously solve the above problems of TCM, acupuncture, and electrical stimulation to help sleep. Given that the dissolvable microneedle sleep aid and the metal microneedle transcutaneous electrical stimulation sleep aid programs integrate the advantages of TCM, acupoint acupuncture, and TES sleep aids and avoid their disadvantages, they are highly promising sleep-aid programs.

In this section, four major directions of medical sleep aids: Western medicine treatment, Chinese medicine treatment, psychology treatment and Chinese medicine psychology treatment—are systematically sorted out, and their mechanisms of action, clinical effects and applicable populations are comprehensively evaluated. Medical sleep aids occupy a central position in the intervention of sleep disorders, but there are significant differences in the theoretical basis, evidence of efficacy and individualized application of different methods.

C. Microneedle Sleep-Aid Techniques

1) Mechanism and Theoretical Model of Microneedle Sleep Aids: To achieve an efficient sleep aid, the mechanism of action must first be clarified. Considering that appropriate acupoint acupuncture has a positive effect on the sleep quality of insomnia patients, it is very important to choose the acupoints to be stimulated. Reference [1], Zhao et al. [107], and Yin et al. [146] pointed out that for traditional acupuncture for sleep, the commonly used acupoints are Anmian, Sishencong, Yintang, Baihui, Shenting, Shenmen, Sanyinjiao, and Neiguan. Stimulating Anmian, Sishencong, Yintang, Baihui, and other acupoints has the effect of promoting sleep and regulating mood, and can also improve depression and anxiety. Stimulating Shenting, Shenmen, Sanyinjiao, and Neiguan can harmonize yin and yang and calm the mind, thus improving sleep. Traditional acupuncture needles are usually long, centimeter scale, and only one needle is applied to each acupoint, but the micro-needle patch is usually an array structure, and each patch usually has dozens or hundreds of needles, and the length of the needles is 100 micrometers or millimeters, so whether it is a soluble micro-needle or a metal micro-needle, the sleep-aiding mechanism is different from that of traditional acupuncture, and the method of selecting acupoints for micro-needle acupuncture is also different, but the relevant research has rarely been reported at home and abroad. However, there is little research on this topic at home and abroad. In addition, most of the current studies qualitatively analyze the mechanism of sleep-aiding by acupuncture from the theory of TCM but not quantitatively from the theory of neuroscience, and the mechanism of the effect of soluble microneedle administration and metal microneedle electrical stimulation on the nervous system is not yet known.

The skin has been considered an attractive site for drug delivery [147] because it avoids first-pass metabolism in the liver and enzymatic degradation in the gastrointestinal tract. However, the stratum corneum of the skin limits the efficiency of transdermal drug delivery, hence, a soluble microneedle is needed to improve drug delivery efficiency [148]. After the drug-loaded dissolvable microneedles penetrate the stratum corneum of the skin to reach the dermis, the drug is gradually released from the encapsulated matrix [149], thus greatly improving the ease and efficiency of drug delivery. There are four main types of microneedles: hollow microneedles, coated microneedles, soluble microneedles, and solid microneedles [150], where soluble microneedles are usually composed of biodegradable polymers, such as carboxymethylcellulose, polyvinylpyrrolidone, polyvinylalcohol, and hyaluronic acid [151], and solid microneedles mainly include silicone microneedles, hydrogel microneedles, and metal microneedles. Since the microneedle patch is an array structure, it reduces the requirement for acupoint localization and avoids the heavy reliance on experience in traditional acupuncture. The dissolvable microneedle drug delivery technique avoids the painful process of boiling and drinking Chinese herbs, and the metal microneedles reduce the impedance of skin contact, thus improving the effect of electrical stimulation. Therefore, dissolvable microneedle drug delivery and metal microneedle electrical stimulation are becoming increasingly popular. The interaction between soluble microneedles and skin is a very complex process due to mechanical nonlinearity, scale effect, and heat transfer effect. Although there are more studies on the processing, functional properties, and test effects of soluble microneedles, there are very few studies on the microneedle-skin mechanical interaction model, drug delivery model, and related numerical simulation methods, which have been reported less frequently [152].

2) Microneedle Design Methods: The design of sleep-aid microneedles includes the design of sleep-aid drug and matrix formulations, the design of herbal active ingredient extraction methods, the design of microneedle size and structure, and the design of microneedle reliability and manufacturability. In terms of the design of sleep-aid drug and matrix formulations for dissolvable microneedles, as well as the design of extraction methods for the active ingredients of TCMs, Qi et al. [153] developed a dissolvable microneedle patch prepared from proline, melatonin, and serotonin, and in vivo experiments in rats showed that the microneedle patches released medicine into the body through the skin and maintained a high concentration. Zhu et al. [154] proposed a microneedle patch formulation of armodafinil, and after treating sleep-deprived mice with this microneedle patch, in vivo pharmacological studies demonstrated that the patch eliminated the effects of sleep deprivation. However, due to the limited effect of melatonin in adults and the fact that armodafinil is an addictive prescription drug [124], [125], [126], there are limitations to these Western drug-soluble microneedles, and there is a need to investigate herbal drug-soluble microneedles. At present, the medicine contained in soluble microneedles reported at home and abroad are mainly based on one or more kinds of monomer Western medicine, and soluble microneedles of TCM for sleep aid have not been reported. Although in recent years, soluble microneedles of TCM for the treatment of dermatological diseases have gradually appeared [155], [156], the relevant studies are also relatively simple, and the medicine contained in the microneedles are one or two active ingredients of traditional Chinese medicinal herbs. However, Chinese medicine emphasizes the systematic regulation of the balance of yin and yang, and the efficacy of each Chinese herbal medicine is not derived from one or two active ingredients but from the superposition of multiple active ingredients (i.e., compounding). Therefore, how to efficiently extract multiple active ingredients from Chinese herbal medicines and remove ineffective ingredients is a very challenging problem. In addition, the parameter design of sleep-aid herbal compounds and dissolvable microneedle formulations for microneedles is extremely challenging because the microneedle drug-carrying capacity is very limited, unlike traditional sleep-aid herbal compounds [128], [157].

In terms of the design of microneedle size and structure, as well as microneedle reliability and manufacturability, Xiu et al. [158] identified the parameters of dissolvable microneedles, such as shape, needle length, spacing, and tip radius, as the key factors affecting microneedle drug delivery. Microneedles that are too short cannot penetrate the stratum corneum, but microneedles that are too long increase the risk of nerve contact leading to pain or puncturing capillaries leading to bleeding. A microneedle with an L/D ratio that is too low affects its depth of penetration into the skin; too high reduces the mechanical properties of the microneedle; and the L/D ratio determines the volume of the microneedle, which affects the drug-carrying capacity. Increasing the microneedle spacing is more favorable for skin penetration, but the number of needles in a microneedle array with a large spacing under the same area is less, and the drug-carrying capacity is smaller. The smaller the tip radius, the smaller the contact area, and the lower the skin penetration force, but also the lower the mechanical strength of the tip, which is prone to buckling. Amiri and Vahidi [159] performed a 3-D simulation of the skin pricking process and calculated the depth of pricking for different times and velocities. Radhika and Gnanavel [160] performed a buckling analysis of dissolvable microneedles to find out the critical buckling load by simulating the buckling of the microneedles. He et al. [161] proposed a herbal dissolvable microneedle and further investigated the mechanical modeling of microneedle penetration and the sleep aid effect, which showed that the microneedle could penetrate the superficial layers of the skin and that the ratio of low-frequency brainwave energy to high-frequency brainwave energy of the subjects was significantly elevated. However, the current parameter design studies are still not systematic enough, especially for the soluble microneedles of TCM, and the related parameter design studies are even less. The studies on analyzing and designing the parameters of microneedles, such as shape, needle length, spacing, and tip radius, by comprehensively considering the feasibility of process manufacturing, the drug loading capacity of TCMs, the drug delivery efficiency, and the reliability of microneedles are almost blank and very challenging. In addition, for metal microneedles, current research focuses on metal microneedle processing techniques for flexible substrates [162], [163], with less research on processing methods for solid metal microneedles [144], and there is a virtual void of research on the reliability of metal microneedles in the use environment of skin oils and perspiration, which is key to the performance of the skin interface.

3) Microneedle Sleep-Aid Control Methods: Microneedle's sleep-aid control methods include the detection and evaluation of sleep-aid effects and sleep-aid closed-loop control methods. In the detection and evaluation of the sleep-aid effect, the current gold standard is PSG, which is a combination of EEG, ECG, EOG, and EMG [164], and it has a high degree of accuracy. However, dozens of electrodes need to be worn by the patient during sleep monitoring, and the process of wearing electrodes is very troublesome and time-consuming. Polylinking has a certain impact on sleep itself, and the unconscious movement during sleep may lead to part of the electrodes falling off, which affects the measurement results. Due to the problems of PSG, such as expensive equipment, uncomfortable wearing, and nonportability, low-cost portable EEG monitoring devices for home use have appeared in recent years [164], [165], which have only a few leads, or even a single lead, and are mainly based on TI's (Texas Instruments) bioelectricity acquisition chip solutions. However, TI's chip solution is not optimal, considering that the EEG signal is extremely weak, only a few microvolts, so noise analysis and circuit optimization are needed to improve the detection accuracy, but there is a lack of relevant research reports. In addition, a large number of studies on sleep stage classification are currently conducted at home and abroad, ranging from multilead to single-lead EEG, and the reported deep learning classification models are more complex and have higher detection accuracy [61], [166]. However, fewer studies have been reported on lightweight classification models that can be computed at the edge of an embedded chip.

In terms of closed-loop control methods for sleep aids, Zhang et al. [167] noted that transcutaneous electrical stimulation of acupoints can improve sleep quality and increase the duration of SWS. Zhao et al. [168] stated that transcutaneous electrical stimulation of cranial ear acupoints can regulate signal propagation in the vagus and trigeminal nerves, thus regulating the CNS and improving insomnia. Kim et al. [169] noted that transcutaneous trigeminal electrical stimulation stabilizes overactive sympathetic nerves, thereby improving sleep quality in patients with insomnia. Zhou et al. [108] showed that transcutaneous electrical nerve stimulation affects melatonin secretion, which regulates and improves the sleep-wake cycle. It can be seen that appropriate electrical stimulation of acupoints is beneficial to sleep aids; however, the currently reported electrical stimulation protocols are all open-loop control protocols, which use electrical stimulation of fixed duration and intensity with no closed-loop feedback during the stimulation process. The sleep-aiding effects of electrical stimulation signals with different pulse widths, different peaks, and different frequencies are different, but there is a lack of relevant studies. In addition, Chinese medicine soluble microneedle sleep aid and metal microneedle transcutaneous electrical stimulation sleep aid are highly potential sleep-aid programs; however, there is currently a gap between domestic and international studies on Chinese medicine soluble microneedle sleep aid, metal microneedle transcutaneous electrical stimulation sleep aid, and the integration of the two sleep aids.

In summary, microneedle sleep aid technology is an emerging, nondrug-dependent sleep intervention method, which centers on the delivery of sleep aid active ingredients (e.g., melatonin, plant extracts) or transcutaneous stimulation of neuromodulatory signals via micrometer-sized needles (usually dissolvable or degradable) to improve sleep quality. However, the research in this field is still in the preliminary exploration stage, and there is almost a gap in the systematic research of related theoretical models, design methods, and control strategies, which urgently requires interdisciplinary cooperation to promote its development.

IV. CONCLUSION

This article utilizes expertise in neuroscience, clinical medicine, biomedical engineering, computer science, mobile health, and human–computer interaction to discuss sleep monitoring and sleep-aid techniques from an interdisciplinary perspective. The principles of state-of-the-art sleep monitoring techniques, multidimensional sleep parameter recognition techniques, and physical, medical, and microneedle sleep-aid techniques are presented. In addition, the advantages and limitations of these techniques are discussed, as well as the opportunities and challenges of emerging techniques. The main conclusions are as follows.

It is usually difficult for a single sensor to simultaneously detect parameters, such as in-and-out-of-bed state, heart rate, HRV, respiration rate, snoring, body movement, and sleep stage, which also tends to lead to misjudgment. Therefore, to improve accuracy, multisensor fusion (e.g., IMU and flexible pressure sensor fusion) for sleep monitoring is a future trend. In the future, in-depth exploration and research are needed to improve the accuracy and comfort of sleep monitoring. In terms of sleep parameter recognition, in-depth exploration and research are needed in the future to improve the accuracy of sleep monitoring parameter recognition and reduce the difficulty and cost of algorithm implementation. From the point of view of research status and development dynamics, sleep problems at home and abroad are becoming more and more serious, but there is a lack of low-cost, comfortable, and effective home sleep monitoring products. The related research on sensor detection and sleep parameter recognition techniques is relatively fragmented, and there is a need for more systematic and in-depth research in the future.

For sleep-aid intervention, from the perspective of research status and development, the combination of TCM soluble microneedle sleep aid and metal microneedle transcutaneous electrical stimulation sleep aid is the trend of future development, with great potential. However, at present, research on the relevant theories and methods is relatively fragmented. In the future, there is a need for more systematic and in-depth research on the theoretical model of the microneedle sleep mechanism, the microneedle design method, and the sleep control method. Besides, the integration of multiple sleep intervention methods is also a trend in technological development.

Although this article provides a comprehensive technical review, it still suffers from the following shortcomings: it focuses on the English literature of the last 5 years, with insufficient inclusion of non-English-speaking countries (e.g., Japanese and Korean traditional medicine studies). The conclusions of the multisensor error analysis and the effect of microneedling on sleep are based on theoretical derivation and lack independent experimental validation. Data privacy (e.g., the risk of cloud storage of sleep EEG) and long-term use safety (e.g., cumulative skin damage from microneedling) are not explored in depth. In the future, we hope that more scholars will conduct research on the missing directions, especially the neuromodulatory mechanisms of emerging technologies, such as microneedling. With the advancement of biosensing, AI and material science, sleep health management will move toward precision, personalization, and noninvasiveness, but it requires academia and industry to work together to promote more emerging techniques landing and standardization.

REFERENCES

[1] N. Littlehales, *Sleep Revolution*. Guiyang, Guizhou: Guizhou Sci. Technol. Press, 2020.

[2] N. Seiji, *The Stanford Method of Efficient Sleep*. New York, NY, USA: Cultural Develop. Press, 2018.

[3] Z. Liyi, *World J. Sleep Med.*, vol. 2, no. 4, pp. 193–196, Aug. 2015.

[4] M. M. J. Nielen et al. “Incidentie en Prevalentie van Gezondheids Problemen in de Nederlandse Huisartsenpraktijk.” 2012. [Online]. Available: https://www.henw.org/artikelen/incidentie-en-prevalentie-van-gezondheidsproblemen-de-huisartspraktijk

[5] “China sleep research report 2023: Sleep duration to be increased, sleep quality to be improved-China science and technology net[EB/OL].” Accessed: Jun. 21, 2023. [Online]. Available: http://m.stdaily.com/index/kejixinwen/202303/a4f8fa7fa06b4d57815f4072d1cdd7ff.shtml

[6] J. X. Wang, Y. Zhang, and Y. Zhang. “China Sleep Study Report 2023.” 2023. [Online]. Available: https://worldsleepsociety.org/membership/societymembership/membersocieties/chinese-sleep-research-society/

[7] Z. X. Zhao, *Sleep Medicine*. New Delhi, India: People’s Health Pub. House, 2016.

[8] *American Academy of Sleep Medicine, American Academy of Sleep Medicine Manual for Interpretation of Sleep and Related Events (Rules, Terminology, and Technical Specifications Version 2.3)*. New Delhi, India: People’s Health Publ. House, 2017.

[9] A. Yoshihisa and Y. Takeishi, “Sleep disordered breathing and cardiovascular diseases,” *J. Atheroscler. Thromb.*, vol. 26, no. 4, pp. 315–327, Apr. 2019.

[10] H. Singh, R. K. Tripathy, and R. B. Pachori, “Detection of sleep apnea from heart beat interval and ECG derived respiration signals using sliding mode singular spectrum analysis,” *Digit. Signal Process.*, vol. 104, Sep. 2020, Art. no. 102796.

[11] E. Pahuja, N. Manjunatha, and C. N. Kumar, “Quality of life in patients with sleep disorders,” in *Sleep and Neuropsychiatric Disorders*. Singapore: Springer, 2022, pp. 613–629.

[12] I. Perez-Pozuelo et al., “The future of sleep health: A data-driven revolution in sleep science and medicine,” *NPJ Digit. Med.*, vol. 3, no. 1, p. 42, 2020.

[13] S. A. Landry et al., “A review of supine position related obstructive sleep apnea: Classification, epidemiology, pathogenesis and treatment,” *Sleep Med. Rev.*, vol. 72, Jun. 2023, Art. no. 101847.

[14] P. K. Stein and Y. Pu, "Heart rate variability, sleep and sleep disorders," *Sleep Med. Rev.*, vol. 16, no. 1, pp. 47–66, 2012.

[15] L. Zhang, H. Wu, X. Zhang, X. Wei, F. Hou, and Y. Ma, "Sleep heart rate variability assists the automatic prediction of long-term cardiovascular outcomes," *Sleep Med.*, vol. 67, pp. 217–224, Mar. 2020.

[16] A. Shokouhmand, N. D. Aranoff, E. Driggin, P. Green, and N. Tavassolian, "Efficient detection of aortic stenosis using morphological characteristics of cardiomechanical signals and heart rate variability parameters," *Sci. Rep.*, vol. 11, no. 1, 2021, Art. no. 23817.

[17] H. Yoon, S. H. Hwang, J.-W. Choi, Y. J. Lee, D.-U. Jeong, and K. S. Park, "Slow-wave sleep estimation for healthy subjects and OSA patients using R–R intervals," *IEEE J. Biomed. Health Informat.*, vol. 22, no. 1, pp. 119–128, Jan. 2018.

[18] S. Roomkham, D. Lovell, J. Cheung, and D. Perrin, "Promises and challenges in the use of consumer-grade devices for sleep monitoring," *IEEE Rev. Biomed. Eng.*, vol. 11, pp. 53–67, 2018.

[19] T. Nakamura, Y. D. Alqurashi, M. J. Morrell, and D. P. Mandic, "Hearables: Automatic overnight sleep monitoring with standardized in-ear EEG sensor," *IEEE Trans. Biomed. Eng.*, vol. 67, no. 1, pp. 203–212, Jan. 2020.

[20] P. Memar and F. Faradji, "A novel multi-class EEG-based sleep stage classification system," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 1, pp. 84–95, Jan. 2018.

[21] J. T. C. Schwabedal et al., "Alpha-wave frequency characteristics in health and insomnia during sleep," *J. Sleep Res.*, vol. 25, no. 3, pp. 278–286, 2016.

[22] F. Deng et al., "Design and implementation of a noncontact sleep monitoring system using infrared cameras and motion sensor," *IEEE Trans. Instrum. Meas.*, vol. 67, no. 7, pp. 1555–1563, Jul. 2018.

[23] Y. K. Wang, H. Y. Chen, and J. R. Chen, "Unobtrusive sleep monitoring using movement activity by video analysis," *Electronics*, vol. 8, no. 7, p. 812, 2019.

[24] P. Jakkaew and T. Onoye, "Non-contact respiration monitoring and body movements detection for sleep using thermal imaging," *Sensors*, vol. 20 no. 21, p. 6307, 2020.

[25] F. Wang, X. Zeng, C. Wu, B. Wang, and K. J. R. Liu, "mmHRV: Contactless heart rate variability monitoring using millimeter-wave radio," *IEEE Internet Things J.*, vol. 8, no. 22, pp. 16623–16636, Nov. 2021.

[26] M. Hur, K. Han, and S. Hong, "Multiple human heart rate variability detection using MIMO FMCW radar with differential beam techniques," *IEEE Trans. Radar Syst.*, vol. 1, pp. 698–706 2023.

[27] H. Hong et al., "Microwave sensing and sleep: Noncontact sleep-monitoring technology with microwave biomedical radar," *IEEE Microw. Mag.*, vol. 20, no. 8, pp. 18–29, Aug. 2019.

[28] M. Baboli, A. Singh, B. Soll, O. Boric-Lubecke, and V. M. Lubecke, "Wireless sleep apnea detection using continuous wave quadrature doppler radar," *IEEE Sensors J.*, vol. 20, no. 1, pp. 538–545, Jan. 2020.

[29] S. Ahmed et al., "Noncontact assessment for fatigue based on heart rate variability using IR-UWB radar," *Sci. Rep.*, vol. 12, no. 1, 2022, Art. no. 14211.

[30] Y. Gu, Y. Zhang, J. Li, Y. Ji, X. An, and F. Ren, "Sleepy: Wireless channel data driven sleep monitoring via commodity WiFi devices," *IEEE Trans. Big Data*, vol. 6, no. 2, pp. 258–268, Jun. 2020.

[31] B. Yu et al., "WiFi-sleep: Sleep stage monitoring using commodity Wi-Fi devices," *IEEE Internet Things J.*, vol. 8, no. 18, pp. 13900–13913, Sep. 2021.

[32] M. N. Markandeya, U. R. Aberyratne, and C. Hukins, "Overnight airway obstruction severity prediction centered on acoustic properties of smart phone: validation with esophageal pressure," *Physiol. Meas.*, vol. 41, no. 10, 2020, Art. no. 105002.

[33] S. Vandana, T. Palla, S. Pallempati, and V. Padavala, "Smart pillow," *Int. J. Anal. Exp. Modal Anal.*, vol. 12, no. 8, pp. 2172–2178, Aug. 2020.

[34] C. K. Weng et al., "Implementation of a wearable ultrasound device for the overnight monitoring of tongue base deformation during obstructive sleep apnea events," *Ultrasound Med. Biol.*, vol. 43, no. 8, pp. 1639–1650, 2017.

[35] Z. W. Li et al., "Snoring detection based on a stretchable strain sensor," *Sci. China Inf. Sci.*, vol. 64, no. 7, 2021, Art. no. 174201.

[36] C. Kuo, Y. Liu, D. Chang, C. Young, F. Shaw, and S. Liang, "Development and evaluation of a wearable device for sleep quality assessment," *IEEE Trans. Biomed. Eng.*, vol. 64, no. 7, pp. 1547–1557, Jul. 2017.

[37] W. R. Pigeon et al., "Validation of the sleep-wake scoring of a new wrist-worn sleep monitoring device," *J. Clin. Sleep Med.*, vol. 14, no. 6, pp. 1057–1062, 2018.

[38] A. J. Boe et al., "Automating sleep stage classification using wireless wearable sensors," *NPJ Digit. Med.*, vol. 2, no. 1, p. 131, 2019.

[39] S. Morra et al., "Ballistocardiography and seismocardiography detection of hemodynamic changes during simulated obstructive apnea," *Physiol. Meas.*, vol. 41, no. 6, 2020, Art. no. 65007.

[40] X. Han et al., "The latest progress and development trend in the research of ballistocardiography (BCG) and seismocardiogram (SCG) in the field of health care," *Appl. Sci.*, vol. 11, no. 19, p. 8896, 2021.

[41] A. Taebi et al., "Recent advances in seismocardiography," *Vibration*, vol. 2, no. 1, pp. 64–86, 2019.

[42] D. Rai et al., "A comprehensive review on seismocardiogram: Current advancements on acquisition, annotation, and applications," *Mathematics*, vol. 9, no. 18, p. 2243, 2021.

[43] M. J. Tadi et al., "Gyrocardiography: A new non-invasive monitoring method for the assessment of cardiac mechanics and the estimation of hemodynamic variables," *Sci. Rep.*, vol. 7, no. 1, p. 6823, 2017.

[44] S. Sieciński, P. S. Kostka, and E. J. Tkacz, "Gyrocardiography: A review of the definition, history, waveform description, and applications," *Sensors*, vol. 20, no. 22, p. 6675, 2020.

[45] Y. D'Mello et al., "Real-time cardiac beat detection and heart rate monitoring from combined seismocardiography and gyrocardiography," *Sensors*, vol. 19, no. 16, p. 3472, 2019.

[46] C. Milena et al., "Linear and non-linear heart rate variability indexes from heart-induced mechanical signals recorded with a skin-interfaced IMU," *Sensors*, vol. 23, no. 3, p. 1615, 2023.

[47] W. Wang et al., "Non-intrusive vital sign monitoring using an intelligent pillow based on a piezoelectric ceramic sensor," *J. Eng. Fibers Fabrics*, vol. 15, pp. 1–11, Dec. 2020.

[48] G. Matar, G. Kaddoum, J. Carrier, and J. M. Lina, "Kalman filtering for posture-adaptive in-bed breathing rate monitoring using bed-sheet pressure sensors," *IEEE Sensors J.*, vol. 21, no. 13, pp. 14339–14351, Jul. 2021.

[49] L. Peng, A. Yin, W. Song, W. Yao, H. Ren, and L. Yang, "Sleep monitoring with hidden Markov model for physical conditions tracking," *IEEE Sensors J.*, vol. 21, no. 13, pp. 14232–14239, Jul. 2021.

[50] Y. Chao, T. Liu, and L. M. Shen, "Method of recognizing sleep postures based on air pressure sensor and convolutional neural network: For an air spring mattress," *Eng. Appl. Artif. Intell.*, vol. 121, May 2023, Art. no. 106009.

[51] S. Rajala and J. Lekkala, "Film-type sensor materials PVDF and EMFi in measurement of cardiorespiratory signals—A review," *IEEE Sensors J.*, vol. 12, no. 3, pp. 439–446, Mar. 2012.

[52] S. Rajala, M. Paajanen, and J. Lekkala, "Measurement of sensitivity distribution map of a ferroelectret polymer film," *IEEE Sensors J.*, vol. 16, no. 23, pp. 8517–8522, Dec. 2016.

[53] J. M. Perez-Macias, M. Tenhunen, A. Varri, S. L. Himanen, and J. Viik, "Detection of snores using source separation on an emfit signal," *IEEE J. Biomed. Health Inform.*, vol. 22, no. 4, pp. 1157–1167, Jul. 2018.

[54] H. Adil, A. A. Koser, and A. Gupta, "Sleep monitoring using laser blood flowmeter," in *Proc. SCEECS*, 2020, pp. 1–4.

[55] Y. Li et al., "Smart optic fiber mattress for animal sleep continuous monitoring based multi-modal interferometer," *J. Lightw. Technol.*, vol. 39, no. 12, pp. 4131–4137, Jun. 15, 2021.

[56] W. Chen, Y. Zhang, H. Yang, Y. Qiu, H. Li, and Z. Chen, "Non-invasive measurement of vital signs based on seven-core fiber interferometer," *IEEE Sensors J.*, vol. 21, no. 9, pp. 10703–10710, May 2021.

[57] J. Y. Kim, C. H. Chu, and M. S. Kang, "IoT-based unobtrusive sensing for sleep quality monitoring and assessment," *IEEE Sensors J.*, vol. 21, no. 3, pp. 3799–3809, Feb. 2021.

[58] F. Li, M. Valero, J. Clemente, Z. Tse, and W. Song, "Smart sleep monitoring system via passively sensing human vibration signals," *IEEE Sensors J.*, vol. 21, no. 13, pp. 14466–14473, Jul. 2021.

[59] N. Yunyoung, K. Yeesock, and L. Jinseok, "Sleep monitoring based on a tri-axial accelerometer and a pressure sensor," *Sensors*, vol. 16, no. 5, p. 750, 2016.

[60] Y. Zhang, A. Xiao, T. Zheng, H. Xiao, and R. Huang, "The relationship between sleeping position and sleep quality: A flexible sensor-based study," *Sensors*, vol. 22, no. 16, p. 6220, 2022.

[61] H. Yue et al., "Research and application of deep learning-based sleep staging: Data, modeling, validation, and clinical practice," *Sleep Med. Rev.*, vol. 74, Apr. 2024, Art. no. 101897, doi: 10.1016/j.smrv.2024.101897.

[62] G. Ye, H. Yin, T. Chen, H. Chen, L. Cui, and X. Zhang, "FENet: A frequency extraction network for obstructive sleep apnea detection," *IEEE J. Biomed. Health Inform.*, vol. 25, no. 8, pp. 2848–2856, Aug. 2021.

[63] S. S. Upadhya, A. N. Cheeran, and J. H. Nirmal, "Thomson multitaper MFCC and PLP voice features for early detection of Parkinson disease," *Biomed. Signal Process. Control*, vol. 46, pp. 293–301, Jan. 2018.

[64] S. P. Jin, X. F. Wang, L. L. Du, and D. He, "Evaluation and modeling of automotive transmission whine noise quality based on MFCC and CNN," *Appl. Acoust.*, vol. 172, Jan. 2021, Art. no. 107562.

[65] Y. E. Erdoğan and A. I. Narin, "COVID-19 detection with traditional and deep features on cough acoustic signals," *Comput. Biol. Med.*, vol. 136, Sep. 2021, Art. no. 104765.

[66] K. K. Lella and A. Pja, "Automatic diagnosis of COVID-19 disease using deep convolutional neural network with multi-feature channel from respiratory sound data: Cough, voice, and breath," *Alexandria Eng. J.*, vol. 61, no. 2, pp. 1319–1334, 2022.

[67] T. K. Dash, S. Mishra, G. Panda, and S. C. Satapathy, "Detection of COVID-19 from speech signal using bio-inspired based cepstral features," *Pattern Recognit.*, vol. 117, Sep. 2021, Art. no. 107999.

[68] S. A. H. Tabatabaei et al., "Methods for adventitious respiratory sound analyzing applications based on smartphones: A survey," *IEEE Rev. Biomed. Eng.*, vol. 14, pp. 98–115, 2021.

[69] L. Verde et al., "Exploring the use of artificial intelligence techniques to detect the presence of coronavirus COVID-19 through speech and voice analysis," *IEEE Access*, vol. 9, pp. 65750–65757, 2021.

[70] A. Tena, F. Clarià, and F. Solsona, "Automated detection of COVID-19 cough," *Biomed. Signal Process. Control*, vol. 71, no. 1, 2022, Art. no. 103175.

[71] M. Aly, K. H. Rahouma, and S. M. Ramzy, "Pay attention to the speech: COVID-19 diagnosis using machine learning and crowdsourced respiratory and speech recordings," *Alexandria Eng. J.*, vol. 61, no. 5, pp. 3487–3500, 2022.

[72] J. L. Xie et al., "Audio-based snore detection using deep neural networks," *Comput. Methods Progr. Biomed.*, vol. 200, Mar. 2021, Art. no. 105917.

[73] H. E. Romero, N. Ma, and G. J. Brown, "Snorer diarisation based on deep neural network embeddings," in *Proc. ICASSP*, Barcelona, Spain, 2020, pp. 876–880.

[74] M. Soltanian and K. Borna, "COVID-19 recognition from cough sounds using lightweight separable-quadratic convolutional network," *Biomed. Signal Process. Control*, vol. 72, no. 1, 2022, Art. no. 103333.

[75] X. Wang et al., "Obstructive sleep apnea detection using ecg-sensor with convolutional neural networks," *Multimedia Tools Appl.*, vol. 79, no. 23, pp. 15813–15827, 2020.

[76] H. A. Rashid, A. N. Mazumder, U. P. K. Niyogi, and T. Mohsenin, "CoughNet: A flexible low power CNN-LSTM processor for cough sound detection," in *Proc. AICAS*, Jun. 2021, pp. 1–4.

[77] N. Petrellis and G. K. Adam, "Cough sound classification based on similarity metrics," in *Proc. TSP*, Jul. 2021, pp. 214–217.

[78] U. Sait et al., "A deep-learning based multimodal system for COVID-19 diagnosis using breathing sounds and chest X-ray images," *Appl. Soft Comput.*, vol. 109, Sep. 2021, Art. no. 107522.

[79] S. Tanwar, Q. Bhatia, P. Patel, A. Kumari, P. K. Singh, and W.-C. Hong, "Machine learning adoption in blockchain-based smart applications: The challenges, and a way forward," *IEEE Access*, vol. 8, pp. 474–488, 2020.

[80] Q. Hu, X. Tang, and W. Tang, "A real-time patient-specific sleeping posture recognition system using pressure sensitive conductive sheet and transfer learning," *IEEE Sensors J.*, vol. 21, no. 5, pp. 6869–6879, Mar. 2021.

[81] Z. Chen and Y. Wang, "Remote recognition of in-bed postures using a thermopile array sensor with machine learning," *IEEE Sensors J.*, vol. 21, no. 9, pp. 10428–10436, May 2021.

[82] S. M. Mohammadi, S. Enshaeifar, A. Hilton, D. J. Dijk, and K. Wells, "Transfer learning for clinical sleep pose detection using a single 2-D IR camera," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 29, pp. 290–299 2020.

[83] R. K. Tripathy and A. U. Rajendra, "Use of features from RR-time series and EEG signals for automated classification of sleep stages in deep neural network framework," *Biocybern. Biomed. Eng.*, vol. 38, no. 4, pp. 890–902, 2018.

[84] A. R. Hassan and A. Subasi, "A decision support system for automated identification of sleep stages from single-channel EEG signals," *Knowl.-Based Syst.*, vol. 128, pp. 115–124, Jul. 2017.

[85] M. M. Rahman, M. I. H. Bhuiyan, and A. R. Hassan, "Sleep stage classification using single-channel EOG," *Comput. Biol. Med.*, vol. 102, pp. 211–220, Nov. 2018.

[86] R. M. Kwasnicki et al., "A lightweight sensing platform for monitoring sleep quality and posture: A simulated validation study," *Eur. J. Med. Res.*, vol. 23, no. 1, pp. 1–9 2018.

[87] K. Kido et al., "A novel CNN-based framework for classification of signal quality and sleep position from a capacitive ECG measurement," *Sensors*, vol. 19, no. 7, p. 1731, 2019.

[88] X. Li, Y. Gong, X. Jin, and P. Shang, "Sleep posture recognition based on machine learning: A systematic review," *Pervasive Mobile Comput.*, vol. 90, Mar. 2023, Art. no. 101752.

[89] Z. Chao, W. Cui, and J. Guo, "MSSC-BiMamba: Multimodal sleep stage classification and early diagnosis of sleep disorders with bidirectional mamba." 2024, *arXiv:2405.20142*.

[90] Z. Chao, W. Cui, and J.Guo. "MSSC-BiMamba: Multimodalsleep stage classication with bidirectional mamba." [Online]. Available: https://openreview.net/pdf/76b8ab53efadfff8a2b775dc0782220c1fe80fec.pdf

[91] X. Zhou et al., "Bit-MAMsleep: Bidirectional temporal mamba for EEG sleep staging," 2024, *arXiv:2411.01589*.

[92] U. R. Acharya et al., "Nonlinear dynamics measures for automated EEG-based sleep stage detection," *Eur. Neurol.*, vol. 74, nos. 5–6, pp. 268–287, 2015.

[93] M. J. Prerau et al., "Sleep neurophysiological dynamics through the lens of multitaper spectral analysis," *Physiology*, vol. 32, no. 1, pp. 60–92, 2017.

[94] Y. Jiao and B. Lu, "An alpha wave pattern from attenuation to disappearance for predicting the entry into sleep during simulated driving," in *Proc. 8th Int. IEEE/EMBS Conf. Neural Eng. (NER)*, 2017, pp. 21–24.

[95] Y. Jiao and B. Lu, "Detecting driver sleepiness from EEG alpha wave during daytime driving," in *Proc. BIBM*, 2017, pp. 728–731.

[96] M. Szypulska, Z. Piotrowski, "Prediction of fatigue and sleep onset using HRV analysis," in *Proc. MIXDES*, 2012, pp. 543–546.

[97] D. Léger et al., "Slow-wave sleep: From the cell to the clinic," *Sleep Med. Rev.*, vol. 41, pp. 113–132, Oct. 2018.

[98] C. Tian et al., "The effects of exercise on insomnia disorders: An umbrella review and network meta-analysis," *Sleep Med.*, vol. 115, pp. 66–75, Mar. 2024.

[99] G. S. Sharma et al., "Yoga therapy versus cognitive behavioral therapy for chronic insomnia (CBT-I)—A randomized equivalence trial, an interim analysis," *Sleep Med.*, vol. 115, p. 196, Nov. 2024.

[100] M. Lee, C. B. Song, G. H. Shin, and S.-W. Lee, "Possible effect of binaural beat combined with autonomous sensory meridian response for inducing sleep," *Front. Human Neurosci.*, vol. 13, p. 425, Dec. 2019.

[101] D. Gao et al., "SWS brain-wave music may improve the quality of deep sleep: an EEG study," *Front. Neurosci.*, vol. 14, p. 67, Feb. 2020.

[102] S. M. Riedy, M. G. Smith, S. Rocha, and M. Basner, "Noise as a sleep aid: A systematic review," *Sleep Med. Rev.*, vol. 55, Feb. 2021, Art. no. 101385.

[103] P. Koomhin et al., "Michelia essential oil inhalation increases fast alpha wave activity," *Scientia Pharmaceutica*, vol. 88, no. 2, p. 23, 2020.

[104] Y. H. Tang et al., "The therapeutic effect of aromatherapy on insomnia: A meta-analysis," *J. Affect. Disorders*, vol. 288, pp. 1–9, Jun. 2021.

[105] N. Sun et al., "The effect of repetitive transcranial magnetic stimulation for insomnia: A systematic review and meta-analysis," *Sleep Med.*, vol. 77, Jan. 2021, pp. 226–237.

[106] X. L. Zhu, Y. P. Ren, S. P. Tan, and X. Ma, "Efficacy of transcranial alternating current stimulation in treating chronic insomnia and the impact of age on its effectiveness: A multisite randomized, double-blind, parallel-group, placebo-controlled study," *J. Psychiat. Res.*, vol. 170, Feb. 2024, pp. 253–261.

[107] F. Y. Zhao et al., "Acupuncture for primary insomnia: Effectiveness, safety, mechanisms and recommendations for clinical practice," *Sleep Med. Rev.*, vol. 74, Apr. 2024, Art. no. 101892.

[108] L. Zhou et al., "The effect of TENS on sleep: A pilot study," *Sleep Med.*, vol. 107, pp. 126–136, Jul. 2023.

[109] S. B. Simons et al., "A randomized study on the effect of a wearable device using 0.75 Hz transcranial electrical stimulation on sleep onset insomnia," *Front. Neurosci.*, vol. 18, Oct. 2024, Art. no. 1427462.

[110] D. E. Kusumandari et al., "Comparison of EEG sleep characteristic with music and aromatherapy stimuli," *J. Phys. Conf.*, vol. 1080, no. 1, 2018, Art. no. 12050.

[111] S. K. Tai and Y. J. Kuo, "Alterations in brainwaves caused by different music genres," in *Proc. iCAST*, 2019, pp. 1–4.

[112] P. Dubey et al., "Effect of music of specific frequency upon the sleep architecture and electroencephalographic pattern of individuals with delayed sleep latency: A daytime nap study," *J. Family Med. Primary Care*, vol. 8, no. 12, pp. 3915–3919, 2019.

[113] H. Danker-Hopfe, H. Dorn, C. Sauter, G. Schmid, and T. Eggert, "An experimental study on effects of radiofrequency electromagnetic fields on sleep in healthy elderly males and females: Gender matters!" *Environ. Res.*, vol. 183, Apr. 2020, Art. no. 109181.

[114] V. B. Dorokhov et al., "Effects of exposure to a weak extremely low frequency electromagnetic field on daytime sleep architecture and length," *Sleep Med. Res.*, vol. 10, no. 2, pp. 97–102, 2019.

[115] S. Andrianome et al., "Disturbed sleep in individuals with idiopathic environmental intolerance attributed to electromagnetic fields (IEI-EMF): Melatonin assessment as a biological marker," *Bioelectromagnetics*, vol. 37, no. 3, pp. 175–182, 2016.

[116] M. M. Ohayon, V. Stolc, F. T. Freund, C. Milesi, and S. S. Sullivan, "The potential for impact of man-made super low and extremely low frequency electromagnetic fields on sleep," *Sleep Med. Rev.*, vol. 47, pp. 28–38, Oct. 2019.

[117] D. Mahanta, H. Bordoloi, and S. J. Saikia, "LabVIEW based smart pillow," in *Proc. ComPE*, 2020, pp. 632–636.

[118] D. Geng, D. Yang, M. Cai, and L. Zheng, "A novel microwave treatment for sleep disorders and classification of sleep stages using multi-scale entropy," *Entropy*, vol. 22, no. 3, p. 347, 2020.

[119] H. M. Bagheri, N. Khanjani, M. H. Ebrahimi, B. Haji, and M. Abdolahfard, "The effect of chronic exposure to extremely low-frequency electromagnetic fields on sleep quality, stress, depression and anxiety," *Electromagn. Biol. Med.*, vol. 38, no. 1, pp. 96–101, 2019.

[120] W. Y. Jin, A. Wang, J. Ma, and Q. Li, "Effects of electromagnetic induction and noise on the regulation of sleep wake cycle," *Sci. China Tech. Sci.*, vol. 62, pp. 2113–2119, Jul. 2019.

[121] F. Dauz, E. Strumban, and R. G. Maev, "Wearable device for increasing the slow wave sleep stage by electrocutaneous stimulation," in *Proc. CCECE*, 2017, pp. 1–3.

[122] M. F. Pengo et al., "Randomised sham-controlled trial of transcutaneous electrical stimulation in obstructive sleep apnoea," *Thorax*, vol. 71, no. 10, pp. 923–931, 2016.

[123] C. S. Wu et al., "Interactions of insomnia and sedative-hypnotic drug use associated with frailty over time among older adults," *Amer. J. Geriat. Psychiat.*, vol. 31, no. 6, pp. 438–448, 2023.

[124] X. J. Zheng et al., "Pharmacological interventions for the treatment of insomnia: quantitative comparison of drug efficacy," *Sleep Med.*, vol. 72, pp. 41–49, Aug. 2020.

[125] K. Choi, Y. J. Lee, S. Park, N. K. Je, and H. S. Suh, "Efficacy of melatonin for chronic insomnia: Systematic reviews and meta-analyses," *Sleep Med. Rev.*, vol. 66, Dec. 2022, Art. no. 101692.

[126] B. Khaledi-Paveh, S. Maazinezhad, L. Rezaie, and H. Khazaie, "Treatment of chronic insomnia with atypical antipsychotics: results from a follow-up study," *Sleep Sci.*, vol. 14, no. 1, pp. 27–32, 2021.

[127] L. Peter et al., "Severity of behavioral addiction symptoms among young adults using non-prescribed sedatives/hypnotics," *Addict. Behav. Rep.*, vol. 17, Mar. 2023, Art. no. 100485.

[128] X. J. Ni et al., "Updated clinical evidence of Chinese herbal medicine for insomnia: A systematic review and meta-analysis of randomized controlled trials," *Sleep Med.*, vol. 16, no. 12, pp. 1462–1481, 2015.

[129] H. Ren et al. "The therapeutic potential of ziziphi spinosae semen and polygalae radix in insomnia management: Insights from gut microbiota and serum metabolomics techniques," *J. Ethnopharmacol.*, vol. 330, Aug. 2024, Art. no. 118255.

[130] N. Ma et al. "Comparative efficacy and safety of Chinese patent medicines for primary insomnia: a systematic review and network meta-analysis of 109 randomized trials," *J. Ethnopharmacol.*, vol. 31, Jan. 2024, Art. no. 119254.

[131] J. Wang et al., "Visualizing research trends and identifying hotspots of traditional Chinese medicine (TCM) nursing technology for insomnia: A 18-years bibliometric analysis of Web of Science core collection," *Front. Neurol.*, vol. 13, Mar. 2022, Art. no. 816031.

[132] X. Ni et al., "Chinese herbal medicine for insomnia: A systematic review of clinical evidence," *Sleep Med.*, vol. 40, no. 1, pp. e240–e241, 2017.

[133] S. A. Nielson et al., "Challenging beliefs for quality sleep: A systematic review of maladaptive sleep beliefs and treatment outcomes following cognitive behavioral therapy for insomnia," *Sleep Med. Rev.*, vol. 72, Jun. 2023, Art. no. 101856.

[134] H. Gong et al., "Mindfulness meditation for insomnia: A meta-analysis of randomized controlled trials," *J. Psychosom. Res.*, vol. 89, pp. 1–6, Oct. 2016.

[135] A. C. Reynolds et al., "Is cognitive behavioral therapy for insomnia (CBTi) efficacious for treating insomnia symptoms in shift workers? A systematic review and meta-analysis," *Sleep Med. Rev.*, vol. 67, Feb. 2023, Art. no. 101716.

[136] Z. Alimoradi et al., "Effects of cognitive behavioral therapy for insomnia (CBT-I) on quality of life: A systematic review and meta-analysis," *Sleep Med. Rev.*, vol. 64, Aug. 2022, Art. no. 101646.

[137] A. Sweetman et al., "The effect of cognitive behavioural therapy for insomnia on sedative-hypnotic use: A narrative review," *Sleep Med. Rev.*, vol. 56, Jun. 2021, Art. no. 101404.

[138] C. Wang et al., "Discussion on the TCM psychological mechanism of insomnia," *Sleep Med.*, vol. 16, no. 1, pp. S191–S192, 2015.

[139] Y. H. Zhang, D. R. Yang, Y. Li, and W. D. Wang. "Effects of Chinese medicine psychological low impedance idea import therapy on patients with depression," *Western Chin. Med.*, vol. 32, no. 5, pp. 60–63, 2019.

[140] X. Y. Lv et al., "Clinical efficacy study of traditional Chinese medicine (TCM) psychological low impedance intention introduction therapy (TIP technique) for the treatment of depression: A multicenter, randomized controlled trial," *World J. Trad. Chinese Med.*, vol. 14, no. 12, pp. 3410–3413, 2019.

[141] X. Yan, W. D. Wang, L. Hong, and C. R. Tang, "Clinical study on the intervention of chronic insomnia by Chinese medicine sleep regulation technology," *World J. Trad. Chinese Med.*, vol. 17, no. 15, pp. 2191–2194, 2022.

[142] P. Prawiroharjo, E. A. A. Santawi, and Y. T. Martono, "Effective reduction of long term benzodiazepine and other drugs usage for insomnia through cognitive behavioral therapy, muscle stretching session, tDCS, binaural beats, and aromatherapy: A case series," *Sleep Med.*, vol. 115, p. 172, Feb. 2024.

[143] T. Li et al., "A dissolvable microneedle patch based on medical adhesive tape for transdermal drug delivery," in *Proc. IEEE 34th Int. Conf. Micro Electro Mech. Syst. (MEMS)*, Gainesville, FL, USA, 2021, pp. 18–21.

[144] J. Li, D. Huang, Y. Chen, and Z. Li, "Low-cost, metal-based microneedle electrode array (M-MNEA): A three-dimensional intracortical neural interface," in *Proc. 20th Int. Conf. Solid-State Sensors Actuators Microsyst. Eurosensors XXXIII (TRANSDUCERS EUROSENSORS XXXIII)*, 2019, pp. 1635–1638.

[145] F. Y. Zhao et al., "Can acupuncture improve objective sleep indices in patients with primary insomnia? A systematic review and meta-analysis," *Sleep Med.*, vol. 80, pp. 244–259, Apr. 2021.

[146] X. Yin et al., "Efficacy and safety of acupuncture treatment on primary insomnia: A randomized controlled trial," *Sleep Med.*, vol. 37, pp. 193–200, Sep. 2017.

[147] S. S. Moon et al., "Microneedle patch as a new platform to effectively deliver inactivated polio vaccine and inactivated rotavirus vaccine," *NPJ Vaccines*, vol. 7, p. 26, Feb. 2022.

[148] J. Yang, X. Wang, D. Wu, K. Yi, and Y. Zhao, "Loaded multifunctional microneedle patches for rapid hemostasis and cutaneous wound healing," *J. Nanobiotechnol.*, vol. 21, p. 178, Jun. 2023.

[149] R. F. Donnelly and E. Larraneta, "Slowly dissolving intradermal microneedles," *Nat. Biomed. Eng.*, vol. 3, pp. 169–170, Mar. 2019.

[150] Z. Sartawi, C. Blackshields, and W. Faisal, "Dissolving microneedles: Applications and growing therapeutic potential," *J. Controlled Release*, vol. 348, pp. 186–205, Aug. 2022.

[151] L. Zhang et al., "Fabrication, evaluation and applications of dissolving microneedles," *Int. J. Pharmaceut.*, vol. 604, Jul. 2021, Art. no. 120749.

[152] B. Newell and W. B. Zhan, "Mathematical modelling of microneedle-mediated transdermal delivery of drug nanocarriers into skin tissue and circulatory system," *J. Controlled Release*, vol. 360, pp. 447–467, Aug. 2023.

[153] Z. Qi et al., "Silk fibroin microneedle patches for the treatment of insomnia," *Pharmaceutics*, vol. 13, no. 12, p. 2198, 2021.

[154] L. Zhu et al., "Application of armodafinil-loaded microneedle patches against the negative influence induced by sleep deprivation," *Eur. J. Pharmaceut. Biopharmaceut.*, vol. 169, pp. 178–188, Dec. 2021.

[155] J. Chi et al., "Chinese herb microneedle patch for wound healing," *Bioactive Mater.*, vol. 6, no. 10, pp. 3507–3514, 2021.

[156] X. Ning et al., "Transdermal delivery of Chinese herbal medicine extract using dissolvable microneedles for hypertrophic scar treatment," *Acta Pharmaceutica Sinica B*, vol. 11, pp. 2937–2944, Jun. 2021.

[157] Z. Y. Ye et al., "Traditional Chinese medicine for insomnia: Recommendation mapping of the global clinical guidelines," *J. Ethnopharmacol.*, vol. 322, Mar. 2024, Art. no. 117601.

[158] X. L. Xiu, G. Z. Gao, Y. Liu, and F. S. Ma, "Drug delivery with dissolving microneedles: Skin puncture, its influencing factors and improvement strategies," *J. Drug Del. Sci. Technol.*, vol. 76, Oct. 2022, Art. no. 103653.

[159] Y. Amiri and B. Vahidi, “Three dimensional simulation of the microneedle penetration process in the skin by finite element method,” in *Proc. 26th Nat. 4th Int. Iran. Conf. Biomed. Eng. (ICBME)*, Tehran, Iran, 2019, pp. 70–74

[160] C. Radhika and B. K. Gnanavel, “Buckling analysis of polymer microneedle for transdermal drug delivery,” *Mater. Today Proc.*, vol. 46, no. 9, pp. 3538–3541, 2021.

[161] C. He et al. “A flexible and dissolving traditional Chinese medicine microneedle patch for sleep-aid intervention,” *Heliyon*, vol. 10, no. 12, 2024, Art. no. e33025.

[162] Y. Hou et al., “Miura-ori structured flexible microneedle array electrode for biosignal recording,” *Microsyst. Nanoeng.*, vol. 7, p. 53, Jul. 2021.

[163] W. Zhou et al., “Wireless facial biosensing system for monitoring facial palsy with flexible microneedle electrode arrays,” *NPJ Digit. Med.*, vol. 7, p. 13, Jan. 2024.

[164] J. Seol et al., “Validation of sleep-staging accuracy for an in-home sleep electroencephalography device compared with simultaneous polysomnography in patients with obstructive sleep apnea,” *Sci. Rep.*, vol. 14, p. 3533, Feb. 2024.

[165] J. B. Wang et al., “Noninvasive ultrasonic drug uncaging maps whole-brain functional networks,” *Neuron*, vol. 100, no. 3, pp. 728–738, 2018.

[166] N. Goshtasbi, R. Boostani, and S. Sanei, “SleepFCN: A fully convolutional deep learning framework for sleep stage classification using single-channel electroencephalograms,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 30, pp. 2088–2096, 2022.

[167] J. R. Zhang, Y. Ruan, X. Wang, Y.-L. You, Z.-F. Yin, and W. Gu, “Effect of transcutaneous electrical acupoint stimulation on sleep quality: A systematic review and meta-analysis,” *Eur. J. Integr. Med.*, vol. 66, Feb. 2024, Art. no. 102338.

[168] Y. N. Zhao et al., “Transcutaneous electrical cranial-auricular acupoints stimulation (TECAS) for treatment of the depressive disorder with insomnia as the complaint (DDI): A case series,” *Brain Stimulat.*, vol. 15, no. 2, pp. 485–487, 2022.

[169] J. Kim, S. Kim, W. J. Lee, J. R. Kim, S. I. Nam, and C. H. Yun, “Effects of at-home transcutaneous electrical trigeminal nerve stimulation on sleep quality in patients with insomnia,” *Sleep Med.*, vol. 115, p. 173, Feb. 2024.

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