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The Meaning of Sleep Quality: A Survey of Available Technologies

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ABSTRACT Sleep is an important part of the human daily routine. Restoring sleep is strongly related to a better physical, cognitive, and psychological well-being. By contrast, poor or disordered sleep leads to possible impairments of cognitive and psychological functioning and to a worsened general physical health. In this context, understanding changes in sleep quality becomes a research imperative that leads to the need for the definition of what restoring or quality sleep means. This understanding of what "sleep quality" means requires a cross-domain investigation. It arises the need for a comprehensive study that offers a complete taxonomy of sleep monitoring systems, with a focus on sleep quality, and that gives useful insights about which combination of metrics, signals, and sleep variables is the best in relation to different categories of users. The proposed study is focused on systematically categorizing the methods and approaches for sleep quality understanding, with an emphasis on technological approaches, including wearable, on-bed, and actigraphy devices. It offers a systematic review for researchers who are interested in sleep quality identification tasks, and highlights strengths and weaknesses of state-of-the-art metrics and solutions in order to suggest the best choice for new potential research challenges in the field. Another important outcome of the proposed work is the study of the impact on the identified signal metrics and solutions of the different target user populations with their specific user requirements.

INDEX TERMS Sleep quality, in-home sensing, sleep diaries, polysomnography, sleep devices, sleep monitoring, physiological parameters, smart health.

I. INTRODUCTION

According to the National Institute of Health, sleep is an important part of the human daily routine and it is as essential to survival as food and water [1]. In fact, restoring sleep is strongly related to a better physical, cognitive, and psychological well-being. By contrast, poor or disordered sleep leads to possible impairments of cognitive and psychological functioning and to a worsened general physical health [2], [3]. For these reasons, understanding changes in sleep quality becomes a research imperative that leads to the need for the definition of what restoring or quality sleep means.

A deep understanding of what "sleep quality" means requires a cross-domain investigation. In fact, the human sleep behaviour, and consequently, its sleep characteristics relies on several factors, both physiological and mental. These aspects should be investigated from both clinical and technical experts, and are related to each human being during every phase of their own life. Even if the term "sleep quality" is commonly used in sleep medicine, there is still a lack of an established definition for the term [4]. It is sometimes used to refer to a collection of quantitative sleep measures (i.e., Total Sleep Time - TST, Sleep Onset Latency - SOL, Degree of Fragmentation - DoF, Total Wake Time - TWT, Sleep Efficiency - SE, and so on), and other times to questions about global sleep quality during a specific period in subjective/self-reported diaries or questionnaires (e.g., Pittsburgh Sleep Quality Index - PSQI) [5]. Furthermore, a key study [6], leveraging the results of two experimental campaigns with surveys about health, well-being, and sleepiness, has shown that average sleep quality is better related to health, affect balance, satisfaction with life, and feelings of tension, depression, anger, fatigue, and confusion than average sleep quantity. In addition, average sleep quality was better related

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to sleepiness than sleep quantity. These results indicate that a focus on sleep quality, in addition to sleep quantity, should be put in research efforts to better understand the role of sleep in daily life.

Besides the inner difficulty with defining the concept of sleep quality, further considerations are needed when we study sleep quality in different types of population, in terms of age, sex, and socio-economic context. Different studies assessed the impact of sleep quality and quantity on different measures of health and well-being for different categories of people, from mothers of infants [7], [8] to medical house officers [9]. When studying the impact of sleep quality, also the age of the target population is a key. In particular, people experience changes both in mental and physical aspects, especially as they grow old. This generally affects the characteristics of the sleep habits: changes in pattern, sleep duration, and quality [10]. Elderly people with aging deals exhibit difficulty of falling asleep, sleep fragmentation and maintaining sleep. According to [11], sleep disturbances increases of 50% for people over 65 years old. Many factors can influence these phenomena in older adults: heart failure, allergies, depression, Alzheimer's disease, social isolation, loneliness, and drug use. Health-care professionals should be aware that the sleep problems of the elderly people are an integral part of life. An accurate sleep monitoring is fundamental in order to detect early signs of sleep deprivation and insomnia, evaluating their sleeping habits, and consequentially implementing mechanisms and systems for preventing and overcoming these problems [12]. But sleep is also crucial for children and adolescents' learning, memory processes, and school performance [13]. Research shows that poor sleep seriously affects learning capacity, school performance, and neuro-behavioral functioning [14]–[16].

Summarizing, sleep quality is an as important as complex construct, making it challenging to be defined and evaluated. In the last decades, an increasing number of studies tried to measure the meaning of sleep quality and how it is related and/or validated with respect to gold standard evaluation methods. In the literature, sleep quality has been assessed using different techniques, including objective (e.g., polysomnography and actigraphy) and subjective/self-reported measures (e.g., PSQI, Consensus Sleep Diary - CSD, Richards-Campbell Sleep Questionnaire - RCSQ, Karolinska Sleep Diary - KSD). Moreover, there are other factors, such as the people's perception of their sleep, that can be provided only by subjective methods. Therefore, current research efforts focus on the methods to identify and quantify the key parameters of sleep quality [17].

From the technological point of view, it is important to notice that recent advances in smart health big data offer increasingly unobtrusive solutions for in-home monitoring that deserve to be investigated. More specifically, advanced sensing techniques are able to capture more aspects related to the human body that can reflect a richer physiological and behavioral state of humans while sleeping and enhance the signal robustness in the detection of the quality of their sleep. Nowadays, wearable and on-bed technologies are able to capture not only movements, like in the standard actigraphy approach, but also physiological parameters (e.g., heart rate and respiratory rate), which makes the gap between gold-standard instruments and in-home commercial devices more and more closer.

The proposed study is focused on systematically categorizing the methods and approaches for sleep quality understanding, with an emphasis on technological approaches, including wearable, on-bed, and actigraphy devices. It offers a systematic review for researchers who are interested in sleep quality identification tasks, and highlights strengths and weaknesses of state-of-the-art metrics and solutions in order to suggest the best choice for new potential research challenges in the field. Another important outcome of the proposed work is the review of the sleep variables for two significant classes of target users, with the goal of showing the ranges of the sleep variable for subjects at different conditions.

The survey is organized as follows: Section II gives an overview of the related works and initiatives on defining the sleep quality; Section III details the human sleep characteristics in terms of quantitative variables, while Section IV introduces the core concepts of objective and subjective sleep quality and how they are evaluated with gold standard instruments. The available technological solutions for monitoring the sleep quality are described in Section V. Section VI shows how the identified key variables for an efficient sleep quality monitoring are affected by the requirements coming from different user categories. Finally Section VII draws the conclusions with an emphasis on the lessons learned from the study.

II. RELATED WORKS AND INITIATIVES

In the last decades, we have seen an increasingly effort in the establishment of sleep medicine as an acknowledged medical specialty. This is demonstrated by the work done all around the world in establishing and promoting sleep studies supported by different associations, foundations, and societies. Among these, the most important are: the National Sleep Foundation (NSF),[1] a U.S. nonprofit organization that promotes public understanding of sleep and sleep disorders; the World Sleep Society,[2] founded in 2016 from the collaboration of the World Sleep Federation (WSF) and World Association of Sleep Medicine (WASM) with the aim to promote and encourage education, research and patient care throughout the World, particularly in those parts of the world where the practice of sleep medicine is less developed; the American Academy of Sleep Medicine (AASM),[3] a United States professional society, established in 1975, for the medical subspecialty of sleep medicine which includes disorders of circadian rhythms; and the American Sleep Association (ASA),[4] an

[1]https://www.sleepfoundation.org/
[2]https://worldsleepsociety.org/about/
[3]https://foundation.aasm.org/about/
[4]https://www.sleepassociation.org/

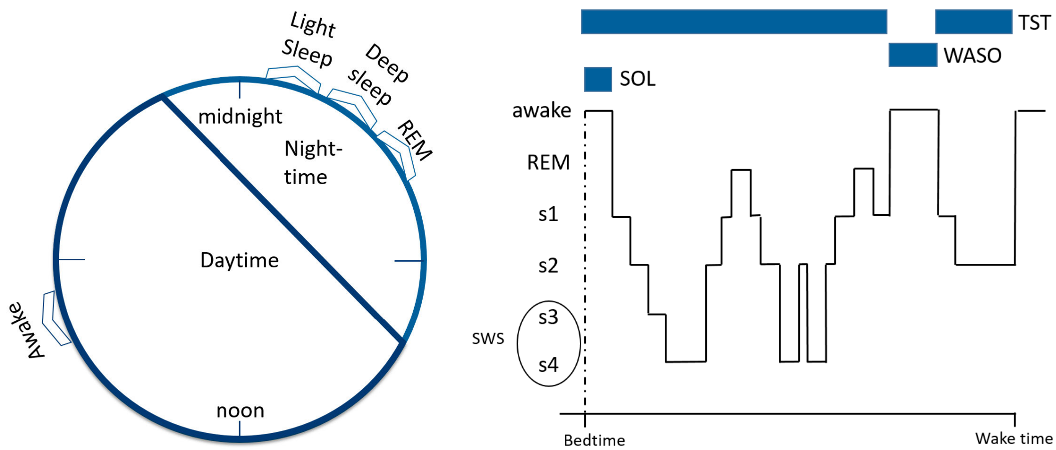

FIGURE 1. (a) The human circadian rhythm and (b) an example of hypnogram.

organization with the primary mission of improving public health by increasing awareness about the importance of sleep and the dangers of sleep disorders. Also in Europe, a big effort has been produced to promote research on sleep and related areas and to improve the care for patients with sleep disorders and to facilitate the dissemination of information regarding sleep research and sleep medicine. Good examples are the activities carried on by the European Sleep Research Society[5] and, in U.K., by the Mental Health Fundation[6] with its specific call for action on sleep.

In the literature, diverse efforts have been made in summarizing the works done in the research area of sleep monitoring, but usually all the available surveys are related to quantifying the sleep in its objective characteristics [18] and signal used to monitor them [19], [20]. A lot of research has been done in providing overviews of the changes in sleep patterns and habits [21], anyway these works are focused on particular types of population in terms of age and sex [22], sleep related disorders [23], on how specific pathologies affect the quality and quantity of sleep [24], or how the a particular life-style influences them [9]. An interesting recent literature review focuses on sleep assessment methods [25] aiming at summarizing and comparing available methods to evaluate sleep. An interesting outcome is given about sensitivity, sensibility, and specificity of subjective and objective methods/technologies with respect to gold standard (subjective methods presenting high sensitivity, while objective methods providing high sensibility, but both with low specificity), highlighting the importance of combining sleep detection methods to produce a synergy between objective and subjective methods. From these considerations, it arises the need for a comprehensive study that offers a complete taxonomy of sleep monitoring systems, with a focus on sleep quality, and that gives useful insights about which combination of metrics, signals, and sleep variables is the best in relation to different categories of users not presenting specific disorders.

[5]https://esrs.eu/

[6]https://www.mentalhealth.org.uk/our-work

III. HUMAN SLEEP CHARACTERISTICS AND QUANTITATIVE VARIABLES

The human being has an internal physiological processes, repeated every 24 hours, that regulates the sleep-wake cycle, as shown in Figure 1a. The description of the human sleep process has involved an huge amount of cross-domain researchers, including clinicians, psychologist, physiologists, technicians, and engineers, during the last sixty years. Historically, the widely accepted sleep classification guidelines was published in Rechtschaffen and Kales (R&K) manual [26] and successive integration and modifications published, for example, in the AASM manual for the scoring of sleep and associated events [27]. A discussion between strengths and weaknesses of the R&K and AASM manual is out-of-the-scope with regard to the goal of this work. While, scope of this section is to present the most important sleep variables in order to characterize the sleep session.

However, analyzing these two manual it is possible to find and to give a short description of which are the variable that mainly are useful to describe the human sleep. Figure 1b shows a typical sleep architecture that is the cyclical pattern of sleep and is composed by the rapid eye movement (REM) and the non-REM (NREM) sleep.

As highlighted in 1b the NREM phase is generally divided in four different stages, namely Stage 1, Stage 2, Stage 3, Stage 4. Generally, the Stage 3 and the Stage 4 are considered together as slow-wave sleep. Recently, the guidelines drawn in the R&K manual has been criticized, in particular due to the low temporal resolution and the insufficient number of stages [28]. In order to overcome these limitations have been introduced new models but they are not widely accepted yet.

The knowledge of the sleep architecture permits to infer new variables that are widely exploited in order to characterize the human sleep (see Figure 1b). Indeed, according to [29]–[31], the R&K criteria allows the identification of conventional sleep parameters: sleep onset latency (SOL), total sleep time (TST), wake after sleep onset (WASO), and Sleep Efficiency (SE). In particular:

TABLE 1. Main sleep variables involved into the sleep quality evaluation.

Variable	Measurement	Definition
Total sleep time (TST)	Minutes	TST is the time between sleep session start and sleep session end minus the time classified as awake
Time in bed (TIB)	Minutes	TB represents the minutes of a users' sleep session
Sleep onset (Son)	Datetime	Son is the time at which the subject falls asleep for the first time
Sleep offset (Soff)	Datetime	Soff is the time at which the subject awakes and does not manage to fall asleep again
Wake after sleep onset (WASO)	Minutes	WASO is the total duration of wake time after Son and it is calculated as the amount of time elapsed between sleep start and sleep end scored as wake
Number of Awakenings (AW)	Number	AW represents the number of events, per night, when the user is awake. Generally, AW are considered awake events if the user is awake for more than 5 minutes
Sleep onset latency	Datetime	SOL represents the time that it takes to accomplish the transition from full wakefulness to sleep, normally to the light sleep
Sleep efficiency	%	SE is commonly defined as the ratio of total sleep time (TST) to time in bed (TB)
Rem sleep	%	Ratio of time spent in REM sleep to TST
N1 sleep	%	Ratio of time spent in N1 sleep to TST
N2 sleep	%	Ratio of time spent in N2 sleep to TST
N3 sleep	%	Ratio of time spent in N3 sleep to TST

- **Sleep Onset latency (SOL)** - In healthy user, it represents the time that it takes to accomplish the transition from awake to sleep.
- **Wake after sleep onset (WASO)** - It is the amount of wake time in minutes during the sleeping period, after sleep onset has been achieved. It can be formulated as:

$$WASO = \sum_{i=1}^{NA} AwD(i)$$

where NA represents the total number of awakenings in between sleep onset and sleep offset, while $Awd(i)$ represents the duration of the i-th awakening.
- **Total Sleep Time (TST)** - It is the sum of all the elapsed time from the sleep onset to the awake; i.e. it is the time spent actually sleeping. It is identified as:

$$TST = TIB - (SOL + WASO)$$

where TIB represents the total *Time in Bed*.
- **Sleep efficiency (SE)** - It is commonly defined as the ratio of total sleep time (TST) and time in bed (TIB):

$$SE = \frac{TST}{TIB}$$

As a conclusion of the sleep variables discussion, in Table 1 are reported all the sleep variables that can be involved into the sleep quality detection process and for each variables is reported the related standard definition. Furthermore, in [31], authors have investigated the association between sleep quality and the subjective perception of sleep parameters. Among these parameters, staying asleep after initially falling asleep is the core variable to identify the perceived quality of sleep. The parameter identified to evaluate the subjective sleep quality is the number of awakenings (NWAK).

IV. OBJECTIVE AND SUBJECTIVE SLEEP QUALITY

The term sleep quality is generally used in the sleep medicine research community, but there is no exact definition widely accepted. Sometimes, it is used to indicate a series of sleep measures, including Sleep Onset Latency (SOL), Sleep Efficiency (SE), Total Sleep Time (TST), Wake After Sleep Onset (WASO), arousals and frequencies of apnea events [4]. These measures may not totally reflect people's sleep experiences, while it is extremely important, in order to better characterize the sleep quality, subjective parameters. Indeed, sleep quality represents some sleep experience's characteristics that are not gathered from other subjective indices. As a result, further study of objective indices may lead to a better understanding of user's sleep experience.

Figure 2 presents a taxonomy of sleep monitoring systems. The sleep monitoring can be analyzed both objective and subjective. The subjective sleep quality is mainly evaluated with sleep diaries and/or questionnaires, while by using clinical devices or commercial devices it is possible to estimate the sleep quality in an objective manner.

In the following sections, methods of subjective and objective sleep quality inferring are discussed. The main idea is to report the state-of-the-art of each category, with the goal of identifying commonalities among different approaches, and drawing guidelines for researchers who are investigating about human sleep quality. While, being this work mainly

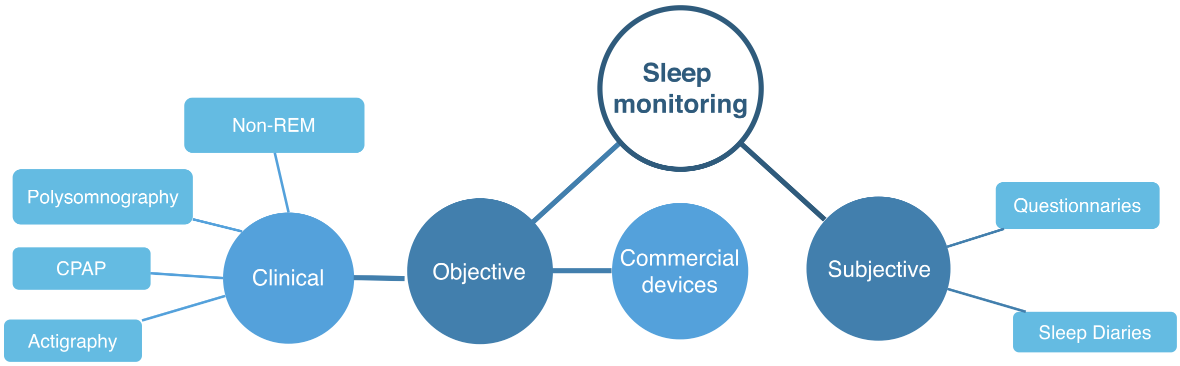

FIGURE 2. Taxonomy of sleep monitoring systems.

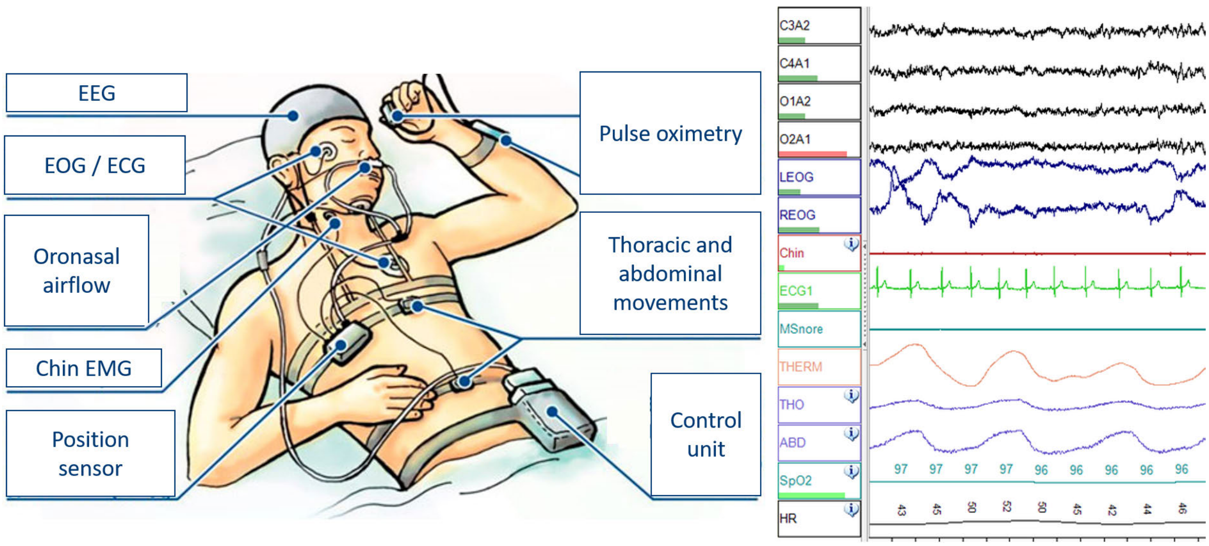

FIGURE 3. A graphical representation of the polysomnography technology from the user point of view and an example of traces obtained from the sensors deployed.

focused on long-term objective sleep quality, the technological solutions with commercial devices deals with in Section V.

A. CLINICAL APPROACHES

Polysomnography (PSG) is considered the gold standard methodology for detecting the sleep pattern by analysing epoch by epoch sleep records [26]. PSG provides measures strictly related to sleep architecture such as Rapid-eye Movement (REM) sleep, Slow-wave Sleep (SWS), stage 1 sleep, and stage 2 sleep. These sleep characteristics cannot be self-reported, but they have been also involved as a part of some indices of sleep quality. A typical graphical form of polysomnography is represented by the hypnogram (1b.b. It represents the human sleep stages, along the time, derived from the scoring of electroencephalogram (EEG), electrooculography (EOG), and electromyography (EMG). The ensemble of these monitoring methods is generally referred as polysomnography. In Figure 3, it is shown a graphical representation of a human being during a polysomnography-based monitoring. The raw signals coming from different technologies are manually scored successively from sleep expert and sleep technicians.

In [32]–[34] authors show, that for some time, individuals show sleep complaints while SOL, WASO, TST, and number of awakenings that are close to those seen in non-complaining individuals.

These parameters, considered together, provide indices of:

- the relative distribution and amount of each sleep stage
- the time and quantity of occurrence of sleep
- the quantity of pathological events as indicators of periodic limb movement disorder (PLMD) and sleep disordered breathing (SDB)

PLMD and SDB have become the standard for both diagnosis and treatment of these conditions. Unfortunately, the nature of sleep is a continuous process and the traditional PSG-derived sleep stage scoring, is a crude indicator able to provide only four categories for a sleep session (stage 1, stage 2, slow wave sleep, REM). The deep nature of sleep, provided using this information, may be useful for individuals who meet diagnostic indices which differ from normal sleepers [32]–[34], but the sleep quality may in general be not correctly addressed.

In literature, several parameters have been used to assessment the sleep quality. The selected parameters general

TABLE 2. Studies about sleep quality identification in clinical settings.

Study	Methods	Subjects involved	Study design	Selected Parameters
Rosipal et al. [35]	PSG recordings, Sleep diaries	148 subjects, age 20–86, no sleep complaints	two consecutive nights, subjective documentation along 14 nights	Total time in bed (h), TST (h), Sleep latency (min), Number of awakenings, WASO, Wakefulness after sleep onset, SE, Stage 1,2,3,4,SWS,REM
Orff et al. [36]	PSG recordings	137 women belonging to normal, controls group, and depressed patients group	over one night	TST (h), SE, Sleep latency (min), WASO, Stage 1,2,3,4,SWS,REM, Rem latency ({%}), REM density ({%}), Number of awakenings, Wakefulness after sleep onset
Lerman et al. [37]	PSG recordings, Actigraphy, Sleep diaries	125 women, diagnosis of Temporomandibular joint disorder	subjective documented their sleep over 14 nights, subjects spent two consecutive nights in sleep lab equipped with PSG	Total time in bed (h), TST (h), WASO SE ({%}), Sleep latency (min) slow-wave sleep SWS ({%})
Spruyt et al. [38]	PSG recordings, Actigraphy	149 healthy school-aged children	over one night	TST (h), WASO (min.) Sleep period time (h), Apneic events and Apnea index, Sleep latency (min)
O'Donnel et al. [39]	PSG recordings, Sleep questionnaries	24 healthy older subjects	over 32 days, three days of baseline followed by a forced de-synchrony protocol	TST (h), Sleep latency (epoch), Stage 1,2,3,4,SWS,REM (min), WASO (min.), SE, final epoch of sleep, number and duration of awakenings

depend on objectives and scenarios of the proposed sleep monitoring systems as well as if the sleep quality has been evaluated from the medical or from the engineering point of view. Table 2 highlight the main variables extracted from studies about sleep quality identification.

Table 2 reports how different studies address the sleep quality analysis, both considering only the PSG methods and a combination within sleep diaries and actigraphy. The table also highlights the sleep parameters manly considered by sleep researchers with medical and psychology backgrounds. As reported in Table 2, the sleep parameters considered in all the selected papers belongs to two different category: sleep stages and derived variables. Into the sleep stage group relies the variables strictly related to the PSG approaches and, at the-state-of-the-art, are not identifiable using not invasive methods. These variables mainly are: Stage 1, Stage 2, Stage 3, Stage 4, Slow-wave sleep, REM. Otherwise, the derived variables mainly are: sleep period time (h), total sleep time (h), wake after sleep on set (m), sleep onset latency (epoch), sleep efficiency, number of awakenings and sleep offset. In the last decade, several effort has been spent in order to detect with high precision these variables using different and less invasive methods with respect to the gold standard approach represented by the PSG. In section V, this work presents an extensive discussion about the state-of-the-art of technological approaches able to identify sleep variables and highlights strengths and weakness of these approaches.

NON-REM EEG FREQUENCY SPECTRAL ANALYSIS

Non-REM (NREM) spectral analysis allows the identification of the frequency content of electroencephalography (EEG) signals gathered during NREM sleep events. These signals are generally elaborate applying Fast-Fourier trasforms (FFTs) in order to obtain measures of the activity considering a set of classic frequency bands in EEG data analysis (from 0.5 Hz to 45 Hz). Consequently, this method generates a continuous analysis of the nature of sleep, using a sleep stage categorisation. The main weakness of this analysis is that the identification of clinically important aspects might be not guaranteed. More specifically, it has been hypothesised that a greater high-to-low EEG frequency ratio during sleep is an indicator of bad sleep in that it is similar to the EEG signal during waking. Furthermore, the EEG pattern has been found to correlate with the cortical activity, as measured with positron emission tomography during sleep [34], [40], [41].

In terms of the relationship of NREM EEG spectral measures and self-reported sleep, NREM EEG activity has been found in patients with insomnia who show no sleep pathology (relative to normal sleepers) on traditional PSG [41]. In [34], authors found no overall relationship of any PSG measure with subjective sleep quality in a group of 30 primary insomnia patients and 20 normal sleepers.

However, the sleep quality is related to greater high frequency activity during NREM sleep among a subgroup of insomnia patients whose traditional PSG indices (SOL, WASO, TST, etc.) are comparable to normal sleepers. These findings suggest the possibility that NREM EEG spectral indices may have some potential as objective indices of sleep quality ratings. However, relatively little research has been carried out with this technique, and the methods are still not standardised.

TABLE 3. Questionnaires and sleep diaries characteristics.

Methods	Type	Structure	Questions about sleep sessions	Questions about daily life behaviour	The Sleep Variables
Athens Sleep Questionnaire (ASQ) [46]	Questionnaires	8 items	8	0	number of awakenings, total sleep time final waketime, perceived sleep quality well-being, sleepiness during the day
Pittsburgh Sleep Quality Index (PSQI) [5]	Questionnaires	19 items	16	3	sleep onset, sleep latency total sleep time, awakenings drugs assumption, sleepiness during the day sleep quality
Consensus Sleep Diary (CSD) [44]	Diary	20 items	10	10	sleep onset, awakenings final waketime, sleep quality
Pittsburgh Sleep Diary (PghSD or PSD) [47]	Diary	24 items	16	8	timing of meals, naps consumption of caffeine/alcohol/tobacco bedtime, sleep latency awakenings, final waketime wake after sleep onset, sleep quality well-being during the day

B. SLEEP DIARIES AND QUESTIONNAIRES

The effort for understanding humans' sleep has traditionally utilised self-report methodology to gather data on perceived sleep quality. As previously described, a discrepancy between objective PSG measures of sleep and subjectively collected information is expected. However, the debate on what exactly is important to measure in order to better characterise sleep is ongoing. Self-report questions on the sleep behaviour have used several different formats. Despite the lack of a standardised format, the sleep diary has been regarded as the gold standard for subjective sleep assessment, and several efforts have been made to understand the validity of self-reported sleep indices. This process may facilitate interpretation and understanding of sleep data. Sometimes, sleep quality is inferred through the evaluation of objectives indices performed from PSG. As reported in section V, these objective parameters are measures such as TST, SOL, WASO, SE, and number of awakenings that, in general, correspond to measures taken from self-report methods (e.g., PSQI, sleep diaries) [42]. Self-report indication present a good level of validity and reliability and these data have to take in consideration but, especially in elderly, age related cognitive changes in memory and/ or executive capabilities may lead to errors in reporting.

Generally, sleep questionnaire and daily sleep diaries contained questions and ask to the user a self-evaluation of different variables of interest: TST, SOL, WASO, SE, difficulty falling asleep, number of awakenings, arising time, bedtime, total time in bed, use of medication and daily naps.

On one hand, diaries provide information on sleep schedule and night awakenings phenomena. However, when it comes to sleep quality measures their validity drops. In clinical research, sleep diaries are generally involved in order to investigate intervention effects. Furthermore, sleep diaries are used to control the quality of the actigraphy data, for example in order to perform artifact removal. On the other hand, sleep questionnaires are particularly useful as a low cost-effective way to gather information on sleep context, sleep patterns, sleep problems and behaviors.

The following discussion focuses on the main self-report diary and questionnaire (i.e., Pittsburgh Sleep Quality Index and Consensus Sleep Diary) used in subjective sleep quality research, exploring their strengths and weaknesses. Table 3 shows the most representative sleep diaries and questionnaires and theirs characteristics in terms of questions about the sleep quality session, the daily activities and the feelings in the morning.

The widely adopted PSQI evaluates the sleep quality variable based on user's evaluation and it includes a series of sleep measures, including sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, the use of sleeping medication, and daytime dysfunction [5].

The PSQI was originally developed to provide clinicians with a valid, standardised measure of sleep quality that could reliably categorise individuals as either good or poor sleepers. This 24-item questionnaire assesses sleep quality using subjective ratings for 7 different components (i.e., sleep duration, sleep quality, sleep efficiency, sleep latency, use of sleeping medication, sleep disturbance, daytime dysfunction). Since its introduction the PSQI has emerged as the de facto gold standard subjective measure of sleep quality. However, as [5] explained, the PSQI does not correlate well with PSG. Indeed, it is suggested that the retrospective nature of the PSQI (a global sleep quality estimate spanning the previous month), could explain its limited agreement with single night PSG recordings. Perhaps PSG recordings averaged over the same period queried by the PSQI would be correlated, but this assertion needs to be empirically confirmed. Since PSQI requires respondents to express answers that are suitable to reflect their sleep during the previous month, it is requested the capacity to accurately remember its recent past [43].

As a consequence, discrepancies between PSQI-based sleep quality evaluation and actigraphy-based systems may be observed, especially in elderly. Basically, PSQI estimation may discriminate between poor and good sleepers. However, this methodology might not identify important clinical changes in users' sleep quality, due to disease and interventions, and to age.

The CSD [44] is the product of collaborations with insomnia experts and potential users. This workgroup designed, tested, and refined a consensus based standardised sleep diary to be used primarily for the purposes of insomnia research, but also for clinical and research applications for both good and poor sleepers. CSD contains 9 questions about: the time of getting into bed, the time at which the individual attempted to fall asleep, sleep onset latency, number of awakenings, duration of awakenings, time of final awakening, final rise time, perceived sleep quality, and an additional space for open-ended comments from the respondent. However, in [44], authors observe that users express limitation about the diary format, and in particular about its ability to address efficiently the sleep experience.

The main point of interest is the verification of sleep parameters gathered using CSD, to prove if they match those of the actigraphy-based data, and to investigate their accuracy. Regarding the consensus sleep diary, as observed in [45], participants tend to under- and overestimate these respective parameters compared to activity tracker data.

In [17] authors suggest, especially for older adults, subjective measures of sleep quality (i.e., the PSQI and CSD) survey different aspects of sleep quality, when compared with objective measures (i.e., actigraphy). As a conclusion, an older adult's perception of their sleep quality is quite different from objective reality.

The two sleep diaries and questionnaires does not pretend to be exhaustive. We have omitted many others diaries and questionnaires because an in-depth discussion about these methods is out-of scope. In Table 3, we highlight the main questions reported into the widely accepted diaries and questionnaires, showing how many variables belongs to the ''sleep session'' group and how many variables are related to the daily life behaviour. Finally, the table show which variables can be inferred from the mentioned diaries and questionnaires.

Mainly, questions about a specific sleep session ask to the user the time to lie on the bed and to go out of the bed, time to fall asleep, numbers of hours, number of awakenings, daily naps frequency, caffeine or alcohol assumption.

V. TECHNOLOGICAL SOLUTIONS FOR SLEEP QUALITY MONITORING

The consumer market offers a variety of sleep monitoring devices able to gather and analyze several physiological parameters. Most of such products are not classified as medical devices, rather products targeted to common users interested in understanding their sleep habits. Under this respect, the goal of this section it to survey the raw signals exploited by the market for assessing the sleep stages as well as the sleep variables described in Section III. It is worth to notice, that this work does not aim to rank the products on the market, rather we aim to survey the technologies available and to list some of commercial products exploiting them.

A first consideration concerns the use of such devices in presence of sleep disorders or diseases. In fact, most of the sleep monitoring devices should be used in absence of disorders during the sleep time. When sleep disorders are present, the sleep pattern can be altered and in turn the quality of the sleep becomes more difficult to assess. In such cases, the overall quality of the sleep depends on the whole clinical conditions of the subject monitored. This is the case of users with a prognosticated insomnia, in these cases the total sleep time variable (see Section III) assumes a completely different concept when compared to a healthy subject with same age and gender.

A second observation is related to the accuracy of the sleep monitoring devices. As a general consideration, the accuracy of such devices increases year after year. This trend is also confirmed by the increasing number of comparative studies published in the last few years [17], [38], [39] showing how the most advanced commercial products provide comparable results with respect to the gold-standard on the sleep monitor. In order to further increase the accuracy, the most advanced solutions are often designed to fuse data obtained from different sensors capturing heterogeneous biological markers. A meaningful example is the detection of the sleep stages. An increase of the accuracy can be obtained by measuring not only the variation of some reference biological markers (such as the heart rate, the heart rate variability and the respiratory rate) but also the body's movements by means of wearable accelerometer.

Another complementary technique for increasing the accuracy of such devices is the use of large datasets with a twofold goal:

- to define *universal* thresholds for determining good and bad sleep habits;
- to profile the users.

For what concerns the first goal, some products available on the market provide to their customers some reference thresholds of the sleep variables. Such thresholds are often used to suggest e.g. the minimum amount of hours to sleep or the ideal time to start sleeping and to wake up in order to keep a healthy life-style. Often, such thresholds are obtained with statistical methods applied to large dataset. The purpose is both to provide to the users useful sleeping tips and also to increase their motivation in using the product. The second goal is to profile the users so that the data collected can be used to further increase the accuracy of the algorithms for monitoring the sleep.

Finally, a last consideration concerns the complexity of comparing outputs provided by the commercial products. This is mainly caused by two factors: on one hand the lack of a standard definition of the meaning of sleep quality leads companies to monitor different and not comparable

TABLE 4. Summary of commercial sleep trackers and the sleep variables monitored.

Raw Signal	Technology	Products	Sleep variables	Sleep score	Features
Heart Rate	Ballistocardiography	Emfit QS™	Sleep stages, TIB, TST	Y	S-CL
		Withings™Sleep	Sleep stages, SOL, WASO, TST	Y	S-CL
		Circa	Sleep stages	NA	S-CL
		Eight Sleep	TIB, Time from wake up to out of bed, TST	Y	S-CL
	Piezolectric	Beddit™	Sleep stages, TIB, SOL, TST, SE, WASO Wake Up Time, Time Sleeping	Y	S-CL
	Piezolectric	Beautyrest	Sleep stages, WASO, TST, Wake Up Time, Time Sleeping	Y	S-CL
	Impedancemetry	Jawbone UP3	TST, TIB, SE, WASO	NA	P-C
	PPG	Garmin®	Sleep stages, TST	NA	P-C
		fitbit©	Sleep stages, WASO, TST	NA	P-C
		Withings™	Sleep stages, SOL, WASO, TST	Y	P-C
		Xiaomi©	Sleep stages, TST	Y	P-C
Body Movement	Actigraphy	Zeeq Smart Pillow	Sleep stages, TST,Wake Up Time, Time Sleeping	Y	S-C
		Thim	Sleep stages, SOL, WASO, TST	Y	P-C
	Noise Detection	iSleep	Sleep stages, TIB, TST	Y	P-CL
Respiratory Rate	Radio Waves	ResMed S+	Sleep stages, WASO, TST	Y	S-CL
	PPG	Oura	Sleep stages, SOL,WASO,TST,	Y	P-C
Brainwaves	EEG	Neuroon	Sleep stages, SOL, WASO, TST	Y	P-C
		Sleep Shepherd Blue	Sleep stages,TIB, TST	Y	P-C

sleeping variables. A common example is the number of sleep stages detected by different products. The stages might vary from 2: wakefulness or sleeping (which includes different sub-stages of the sleeping period) to 5 stages: wakefulness, sleeping, REM, N1, N2 and N3. On the other hand, the algorithms used to monitor the sleep are often protected by patents, therefore it is not possible to fully understand how the sleep variables are computed and hence the possibility of comparing different outputs.

In order to review the techniques, we present in Figure 4 a summary of the most used raw signals for assessing the sleep quality. We refer to a raw signal as any kind of data that can be tracked with sensing units. Such units can be contact-based, meaning that the user must wear the device or, alternatively, contact-less. Table 4 summarizes the commercial sleep trackers that we reviewed, as well as the sleep variables that they can monitor. Our survey starts with a review of the Human Nervous System, in order to understand why some of the raw signals in Figure 4 are so crucial for the sleep monitoring. Then, for each of the signals, we describe how they can be exploited and the commercial products based on them.

A. SIGNALS FROM THE HUMAN BODY

The Human Nervous System (HNS) is sketched in Figure 5. It is responsible of transmitting signals from and to different parts of the body. The HNS consists of two subsystems: Central and Peripheral. The Central is responsible for receiving and analysing signals from the environment both from inside and outside the organism with the goal producing the appropriate responses. Differently, the Peripheral subsystem captures stimuli coming from the organism and it interacts with the Central subsystem. The Peripheral is further divided in Voluntary and Autonomic Nervous System (ANS). The ANS is responsible of all the unconscious but vital activities of the human body by propagating impulses for their regulation. Among the activities, the ANS is responsible for maintaining the cardiovascular process of the body. The ANS is split in two distinct parts: Sympathetic Nervous System (SNS) and Parasympathetic Nervous System (PNS). The SNS is activated to allow the body to react to stressful events due to physical and metal/cognitive tasks. Differently, the PSN activates mainly during the resting periods in order allow the body to relax and recover. SNS and PNS modify in a different way the cardiovascular and the respiratory rate [48], [49], in particular the SNS can increase the heart rate, the stroke volume as well as the respiratory rate while the PNS can decrease the heart rate and the respiratory rate.

B. HEART RATE

Heart Rate (HR) and it variability (HRV) are two of the most exploited signals used to measure the quality of the sleep. The cardiac cycle consists of a sequence of heart beats, a contraction followed by a relaxation period of the heart. During the contraction period, the heart pumps blood out of the heart to the body organs, while during relaxation period the blood coming from the veins re-fills the heart. The number of heart beats happening in one minute is named HR expressed in bpm (beat per minute). A graphical representation of HR ad HRV is shown in Figure 6. The figure shows an example of ECG's trace (the red line) with a reference to the typical phases of the cardiac cycle (P, Q, R, S and T). The heart beat is denoted with the letter R. The time variation between

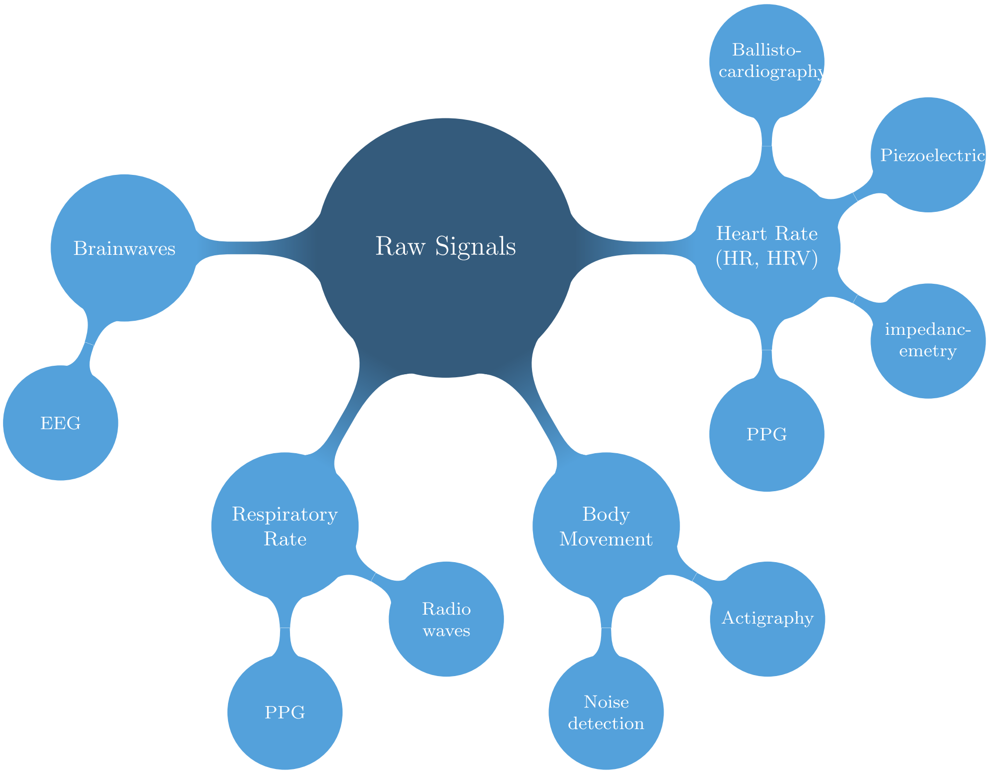

FIGURE 4. Classifications of the raw signals used to monitor the sleep quality.

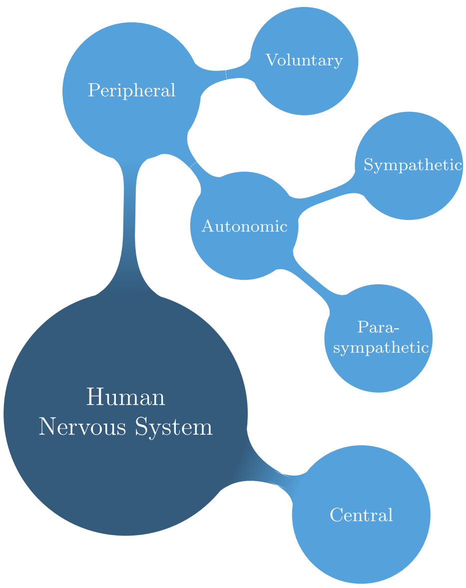

FIGURE 5. The human nervous system.

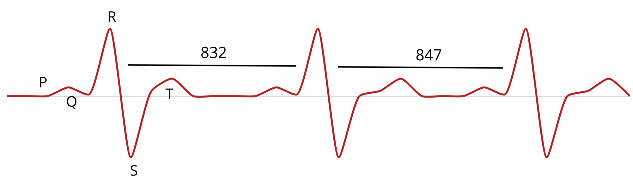

FIGURE 6. HR and HRV.

two consecutive R spikes is the heart rate variability, HRV. As previously reported, HR and HRV vary along with the time. In particular, it is well accepted that HRV reflects the ANS activity as discussed in [50].

For the purpose of the sleep monitoring, HR and HRV can be used to infer when a person is resting. In fact, when the PNS dominates (resting period), generally HR decreases wile HRV increases. Conversely, when the SNS dominates (activity period) HR increases while HRV decreases [51]. Therefore, the key-idea for exploiting HR and HRV is to track the heart rate and to identify time intervals during which HR and HRV vary as expected, as evaluated in [52], [53]

In order to track HR an HRV it is possible to use several techniques, of them we cite the ballistocardiography, piezoelectricity, impedancemetry and the photoplethysmogram (PPG) as shown in Figure 4.

The ballistocardiogram (BCG) measures the mechanical forces generated from the human body, in particular the forces caused by the cardiac cycle and the blood circulation. The sequence of contractions and relaxations of the heart gives rise to forces that reflect to as a recoil effect on the human body. The BCG aims at measuring such recoil effect on the body in order to detect HR, HRV and the Respiratory Rate along the time. The forces propagating longitudinally along the body are the strongest and hence the ones typically captured by such devices. BCG have been designed for different settings: wearable, weighting scale and bed-based devices as reviewed in [54]. On them, we focus BCG designed for deployment of the bed since such products are less invasive, easy to install and with a comparable accuracy with respect to polysomnography. BCG bad-based are generally pads to be deployed under the mattress or to be attached directly to the bed frame, they are generally equipped with accurate accelerometers (often tri-axial). It is worth to notice, that BCGs bed-based suffer of several drawbacks. Firstly, the presence of two or more subjects on the same bed might cause inaccuracies while measuring the HR variables. Secondly the bed sheet or blankets can reduce the sensitivity of the device. Finally, the biological markers detected by BCG (HR, HRV, Respiratory Rate) are subjective, therefore such devices require a calibration setup before collecting the data.

The Emfit QS™ solution [55]–[57] is based on a thin strip to put under the mattress. The strip is able to measure a number of variables such as sleep stages, stress and recovery, apnea scoring, bed exit and occupancy as well as "repetitive muscle jerking".[7] Emfit QS™ is not only designed for people interested in their sleep habits, but also it addresses athletes and sportsmen/women interested in assessing their daily performances. On the same line, the Withings™ Sleep is a strip to be places underneath the mattress. It provides features to assess the quality of the sleep, the snoring detection, HR tracking as well a custom sleeping program. The sensors integrates with the IFTTT (If This Then That) so that to automatize some common actions such as dimming lights or turning up the thermostat. Circa comes as an alarm clock which offers several features for increasing the quality of the sleep and the sleep habits. Optionally, it can be attached via USB with a BCG sensor to install under the mattress. The variables measured are more designed to capture long-term trends, rather than short ones. Another commercial products still based on BCG is the Eight Sleep®. Differently from the other products, it comes as a mattress cover to be installed under the bed sheets. The cover senses the environments (temperature, humidity and noise level) as well as heart and breathing rate and movements. The smart covers can be integrated with Alexa system, so that to configure some scenarios, such as planning the wake time with vocal commands.

Another approach for detecting HR and HRV is through piezolectric sensors which are able to detect and to measure the mechanical deformations of some materials. Piezolectric-based sleep trackers are generally based on thin strip to put under the mattress able to measure such deformations and, in turn, to recognize the bed occupancy and/or some biological markers such as HR and HRV. This is the case of the Beddit™ Sleep Monitor. It comes with a thin sensor strip equipped with an USB adapter for recharge. It tracks the sleep stages, sleep variables (ie. sleep time, bedtime, time to fall), stress level, snoring, HR variables (average, max and min), breathing rate as well as some environmental values such as the temperature and humidity of the room. Still based on piezolectric sensors, Beautyrest® Sleeptracker® is a set of pads to place under the mattress. Pads monitor the respiration and heart rate, the sleep stages and "body movement and interruptions" not only for one person, but also for two people simultaneously. The hardware is composed by one or two pads (for tracking one or two people) wired connected to a processing box. The box collects the data and send them via WiFi connection.

Impedance cardiography is a different techniques that can be used to also track HR. It consists in measuring the changes in time of the electrical conductivity of the some parts of the body. Such variations can be used to infer some dynamics of the heart such as its rate. The Jawbone UP3 is a smart wristband exploiting such technique. It is also equipped with a tri-axial accelerometer able to capture movements of the user, with the goal of detecting and measuring the sleep stages.

A last technology for tracking HR, and hence to infer quality of the sleep, is the PPG. This technique is based on plethysmogram to measure the blood volume changes along the time, which is correlated with the heart rate. PPG can be adopted to measure not only the heart rate, but also pulse transit time, blood pressure and respiration [58]. This technique consists in illuminating capillaries in a skin region with a set of lights (on most of the commercial devices, a set of three green lights). The photodetectors detect the amount of reflections of the light which varies with the cardiac cycle. In particular, when the blood volume increases (the arteries contract) the amount of reflected light rises (high reflection of arteries), while when the blood volume decreases (the arteries swell) the amount of reflected light falls (low reflection of the arteries). The variation between contraction and swell is generally around 2%. The leds illuminate the skin by using different wave forms so that to being able to measure at different conditions: skin tone, thickness, and morphology. Similarly to piezoelectric sensors, PPG sensors have been miniaturized so that to be installed on wearable devices such as wristbands or smart watches. Accuracy of PPG sensors for measuring HR and HRV is discussed in [59], [60]. Under this category, falls most of the smart wristbands available on the market. Some notable examples are: Garmin®,[8] fitbit©,[9] Withings™, [10] Xiaomi©.[11] It is worth to notice that most of the sleep trackers based on PPG sensors, also analyze the body movements (see Section V-C) in order to increase the accuracy of the sleep variables.

C. BODY MOVEMENTS

Tracking the sleep can be achieved by also analysing the body movements. The key idea comes from the observation that movements, generally, reduce during the resting periods with respect to active ones.

For the purpose of the sleep monitoring, the body movements are analyzed not only to infer when a subject is resting

[7] https://www.emfit.com/emfit-mm-seizure-movement-monitor

[8] examples of product series with support for HRV: vivoactive®, Forerunner®, vivosport™, vivosmart®, vivomove®, fenix®.

[9] examples of product series: Fitbit Alta HR™, Fitbit Charge 2,3™, Fitbit Versa™, Fitbit Ionic™

[10] examples of product series: Withings Move, Pulse HR

[11] examples of product series: Mi Band Pulse

or not, but also to measure some sleep variables like: total sleep time, bedtime and rise time. We mention two techniques exploiting the body movements: actigraphy and noise detection as reported in Figure 4.

Actigraphy is a well accepted method for tracking the sleep with a non-invasive method. It consists in analyzing data collected from inertial sensors which can reveal the body motions in a seamless way [61]. Such sensors are available on smart watches, wristbands, smart rings and other kinds of wearable devices. Actigraphy is considered a reference point for the sleep tracking, in fact the subjects monitored are required to only worn a wearable device for a time period. More generally, the strength of actigraphy-based systems is the low impact on the user daily life and their low cost. On the other hand, the major weakness of this method is its limitation in distinguishing if the absence of movements is caused by a sleeping period or not. This phenomenon leads to, for example, a delay in computing the Sleep Onset Latency variable (SOL, see Section III and to an overestimation of the number of night-time awakenings (which are seen as the primary features of insomnia) [62], [63].

Wearable devices for actigraphy, and in particular wrist-worn devices, have been validated through the comparison with polysomnography [61], [64]. The work [65] provides an interesting study focused on the validity of actigraphy. The author clearly explains how the actigraphy had become a major tool for the assessment of the sleep analysis. Furthermore, the work reports several studies on the validity of actigraphy, especially in assessing sleep-wake scoring.

In [66], the authors recommend the usage of actigraphy-based system concurrently with CSD methodologies, in order to identify periods during which users are attempting to sleep. This combination of CSD and actigraphy is currently accepted as an alternative to the PSG methodology [67]. Actigraphy devices may be used to gather objective sleep quality measurements in a natural environment allowing a comparison with the PSQI. In [68], the authors collect the PSQI scores in several settings of duration up to 7 days, the subjects involved are 53 young and 59 old adults. The authors also collects information from the actigraphy as well as information obtained from sleep diaries with the goal of measuring the correlation among such techniques. As a result, authors show that the global PSQI scores do not correlate significantly with actigraphy in younger or older adults, while PSQI scores correlate with the sleep diary entries. In [69], the authors analyze the data collected with actigraphy-based systems. Authors notice and recommend to extend the data collection to 14 days of recordings in order to take into account day-to-day and week-to-week variability.

Commercial products based on actigraphy techniques are often wristbands or smart watched equipped with accelerometers and other sensors tracking movements in a seamless way. This is the case of most of the products already surveyed in Section V-B that also exploit PPG sensors (ie. products from Garmin®, fitbit©, Xiaomi©, ActiWatch®2 and Spectrum [70]). Not only the wristbands can be used to detection motions, but also pillows equipped with sensing units. This is the case of Zeeq Smart Pillow provisioned with a 3-axis gyroscope and accelerometer able to track the sleep. A different approach consists in wearing a ring as proposed with the Thim™ ring [71], [72]. The ring is designed to increase the sleeping experience by following the Intensive Sleep Retraining (ISR). The ring also tracks the sleep with by analyzing the body's movements.

Movements of the body can also be detected through microphones. The noise produced by the rotations of the body during the sleep can be used to infer sleep-waking periods. The Sleep Cycle is a mobile app designed to track the sleep by exploiting sensors available on the smart phone. It is possible to track the sleep with accelerometers or microphone. In the second case, the microphone needs to be oriented toward the user's head so that to record properly the noise.

D. RESPIRATORY RATE

The respiratory system in charge of implementing the exchange of oxygen and carbon dioxide. The system is characterized by two phases: inhalation that delivers oxygen into the lungs and exhalation that releases carbon dioxide. The two phases repeat sequentially in a involuntary way. The frequency of such phases is referred to as respiration rate (RR) while its variation in time is referred to as respiration rate variability (RRV). RR and RRV vary during the day according to resting or active periods. As for example, during physical activities RR increases in order to increase the volume of oxygen to deliver to the muscles, differently during resting period RR decreases (generally in the range of 11 to 20 breaths per minute). RR and RRV can be further exploited in order to analyze sleeping periods [73]–[75]. Some commercial devices analyze RR with several techniques, such as ultra low power radio waves, PPG or with microphone. The ResMed S+© a contact-less device designed to track upper body movements as well as some environmental parameters such as light, temperature and noise level. The device detects the inhalations and exhalations, rations of the body, arm twitches and shrugs. Such movements are detected with ultra low power radio waves with a technique similar to the one used by bats: the echo location. The device ''transmits a short pulse of radio waves at 10.5 GHz and then listens for the echo of the pulse''. Movements of the body modifies the phase of the echo changes, such changes are then converted into signals reflecting the movements [76].

The Oura© ring exploits PPG to infer the Respiration Rate from the blood volume pulse [77], [78]. In particular, inhalations accelerate the heart rate while exhalations decelerate it, and the blood volume modifies accordingly during the two phases. The ring adopts infrared lights at the rate of 250 Hz in order to detect variations of the blood volume at the fingers. The Oura© ring analyzes also other biological markers such as HRV, to increase the accuracy.

E. BRAINWAVES

Differently from all the other raw signals, the brainwaves have been also used to detect resting periods. There exist several techniques to track the brainwaves, among them we cite the electroencephalogram (EEG). The human brain is composed by milions of neurons emitting low-voltage signals, the EEG is based on the analysis of such neuro-signals using electrodes placed on the scalp. The key observation is that the frequency of the signals emitted by the brain changes with the brain state. As for example, humans during the deep, dreamless sleep, non-REM sleep, unconscious emit signals ranging from 0.1 Hz to 3Hz (Delta waves), while during higher mental activity the frequencies range from 30 Hz to 100 Hz (Gamma).

Some commercial products aim at analysing the brainwaves in order to track the sleep. Among them we cite Sleep Shepherd Blue and the Neuroon headbands. Sleep Shepherd Blue is equipped with EEG sensors and tri-axial accelerometers for monitoring the sleep stages and two speakers in order to increase the sleeping experience [79].

F. SELECTING A SENSING TECHNOLOGIES FOR THE SLEEP MONITORING

We finally draw some considerations concerning the technologies that we reviewed for the sleep monitoring as reported in Table 4. As a first consideration, we cannot define the optimal solution of the sleep monitoring. Each of the technologies presented presents some features that have to be considered during the selection of the proper product. To this purpose, we identify two orthogonal aspects helpful for the selection of the proper technology (as reported in the last column of Table 4):

- Static (S) / Portable (P): static devices require a stationary deployment on the environment with (often) a calibration procedure. Portable, generally, devices come in the form of wristbands, smart watches or mobile apps;
- Contact (C) / Contact-less (CL): Contact devices require a direct contact with the subject monitored, as for example the skip contact. Contact-less devices exploit wireless signals for the monitoring purpose.

The advantage of a static device is its integration with the daily routine of subjects. In fact, once the device is properly installed, the subject is not required to perform any other action. This aspect is relevant for long-lasting monitoring periods during which is it important to reduce an explicit user intervention. Moreover, static devices might be the best solution for those subjects with low confidence of high-tech instrumentation. Differently, portable devices require an explicit user intervention in order to bring/wear the device during the sleeping period and to recharge the device periodically. However, such devices often provide extra functionalities, such as alarm clock, social media notifications as well as sport and activity tracking. Subjects are therefore encouraged to bring the device all-day-long, with a potential more accurate screening of the subject.

Contact devices require a direct contact with the subject. This is the case of PPG, EEG and Actigraphy technologies. The main advantage is the possibility of sampling accurately those physiological and/or mechanical signals relevant for assessing the sleep quality. However, as also mentioned previously, they might be perceived from the subjects as non-transparent devices. Contact-less devices overcome such limitation by offering an unobtrusive approach. Subjects are not required to wear or touch the device, and such aspect can increases its acceptability with specific subjects. However, their main disadvantage is related to surrounding environment. In fact, some products require to not alter the environmental conditions, such as the noise intensity, the lighting conditions and the position of the sensing device.

VI. SLEEP VARIABLES FOR DIFFERENT CATEGORIES

The sleep variables presented in Section III are extremely subjective. They vary according to multiple factors such as the healthy conditions, age, gender, job activities, nutrition and the life style. In this section, we survey the results of some significant works [80]–[82] with the objective of showing how sleep variables change for two different subjects. Our goal is not to compare heterogeneous subject's classes, rather it is to show the ranges of the sleep variable for subjects at different conditions.

To this purpose, we consider healthy subjects (see Section VI-A) and athletes (see Section VI-B). On the first case, we report some meaningful results for the sleep variable of healthy subjects split in three categories: young adults, adults and older adults, as originally presented in [80], a relevant work on this research field.

On the second case, we consider individual and team athletes of different disciplines, as originally presented in [81], [82].

A. SLEEP VARIABLES ACROSS DIFFERENT AGES

We report a synthesis of how some sleep variables change across healthy subjects on three categories: young adults, adults and older adults. For each of the categories, we report Sleep onset latency, Number of awakenings, Wake after sleep onset and Sleep efficiency with some possible ranges. A summary of the results presented in [80] are shown in Table 5. It is worth to notice, that authors of [80] observe that among young adults, adults and older adults, literature agrees that elevated REM sleep (i.e., $\geq$41) is not correlated to a good sleep quality.

B. SLEEP VARIABLES IN ATHLETE SUBJECTS

Sleep is an crucial factor for athletes both during training and race periods. In fact, the sleep time is when when body regenerates after stressful training sessions. Sleep can be considered as a complementary attitude of athletes in order to increase fitness and increase the race readiness. Without appropriate sleep habits, the workload during the training sessions might be not beneficial for the body leading also to injuries or decrease of the performance. We report in section

TABLE 5. Sleep variables across different Ages.

Variables	Ranges in young adults	Ranges in adults	Ranges in older adults
Sleep Onset Latency	appropriate: from 0 to 30 minutes uncertain: from 31 to 45 minutes inappropriate: from 46 to more than 1 hour	appropriate: from 0 to 30 minutes uncertain: from 31 to 45 minutes inappropriate: from 46 to more than 1 hour	appropriate: from 0 to 30 minutes uncertain: from 31 to 1 hour inappropriate: more than 1 hour
Number of Awakenings	appropriate: from 0 to 1 uncertain: from 2 to 3 inappropriate: more than 3	appropriate: from 0 to 1 uncertain: from 2 to 3 inappropriate: more than 3	appropriate: from 0 to 2 uncertain: 3 inappropriate: more than 3
Wake After Sleep Onset	appropriate: from 0 to 20 minutes uncertain: from 21 to 40 minutes inappropriate: more than 40 minutes	appropriate: from 0 to 20 minutes uncertain: from 21 to 40 minutes inappropriate: more than 40 minutes	appropriate: from 0 to 30 minutes uncertain: from 31 to more than 1 hour
Sleep Efficiency	appropriate: from 85% to 100% uncertain: from 65% to 84% inappropriate: less than 65%	appropriate: from 85% to 100% uncertain: from 75% to 84% inappropriate: less than 75%	appropriate: from 85% to 100% uncertain: from 75% to 84% inappropriate: less than 75%

TABLE 6. Sleep variables in Athlete subjects.

Variables	Ranges in Individual Sports	Ranges in Team Sports
Sleep Onset Latency	min 12.1 $\pm$ 14.9 (cycling) max 40.1 $\pm$ 38.5 (swimming)	min 8.3 $\pm$ 1.6 (rugby) max 21.2 $\pm$ 20.9 (basketball)
Wake After Sleep Onset	min 11.6 $\pm$ 4.4 (racewalking) max 22.7 $\pm$ 9.2 (swimming)	min 11.9 $\pm$ 3.8 (basketball) max 19 $\pm$ 5.1 (Australian rules football)
Sleep Efficiency	min 83.7 $\pm$ 5.4 (mountain bike) max 91.1 $\pm$ 5.7 (racewalking)	min 85 $\pm$ 4.9 (Australian rules football) max 87.3 $\pm$ 5.2 (rugby)
Time in Bed [hours]	min 7.9 $\pm$ 0.8 (triathlon) max 8.8 $\pm$ 0.8 (moutain bike)	min 8.3 $\pm$ 1.6 (rugby and football) max 8.9 $\pm$ 1.1 (basketball)

a summary of the results originally presented in [81] in which authors present an interesting study of sleep/wake behaviours in individual and team athletes. Table 6 summarizes minimum and maximum values of 4 reference sleep variables: Sleep onset latency, Wake after sleep onset, Sleep efficiency and Time in bed.

VII. LESSONS LEARNED AND CONCLUSIONS

Monitoring the human sleep is a hot topic both in the research and industrial communities. Advanced sensing techniques may fill the gap between traditional clinical approaches and commercial in-home devices for sleep tracking. This goal is ambitious and can led to enhance the human well-being from a short-term and a long-term perspective. Recently, thanks to the intelligent computation techniques advances and the availability of biomedical devices, many solutions have been presented. At the state-of-the-art, many of these proposals are promising and try to clarify the complexity of the physiological states of humans by applying a multi-domain approach involving data, applications, models and biology.

This survey reviews from a technological point of view the most recent products and techniques used to monitor and analyze the sleep. We first present the most common sleep variables used and then we survey products available on the market designed to monitor and infer such variables. We finally provide some reference values for the sleep variables for two target users at different conditions.

We finally propose a list of take-away messages we derive from this survey work. The goal is to support researchers interested in sleep monitoring to identify possible future directions and challenges:

- Commercial sleep tracker devices exhibits significant differences in sleep stages identification when compared with gold-standard devices.
- Commercial devices are not able to objectively assess sleep disorders. If sleep disorders are detected, commercial devices can produce false reassurances.
- Research-grade devices, especially ballicardiography-based systems, are promising tools to fill the gap between clinical and commercial devices.
- At the state-of-the-art, the most promising approaches involve multi-sensor algorithms able to capture and correlate heterogeneous biological signals.
- An increase number of works move towards the collection of dataset for the validation purpose.
- Commercial sleep trackers are perceived as useful tools for most of the end-users. Moreover, in case of healthy subjects, the literature provides well-known ranges for the sleep variables useful to motivate end-users in paying attention of their sleep habits.

However, we consider that most of the technologies presented in Section V are still in their youth. We consider that in the near future, the sleep trackers could be much more diffused and widely adopted when validation tools and techniques will be agreed among all the stake-holders. In particular, we consider that such limited diffusion depends from two main barriers. On one hand, the absence of a reference and accessible sleep dataset and, on the other hand, the lack of common protocols for the validation. Both of the aspects reduce the possibility of comparing different techniques at similar conditions.

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