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SMART MATTRESS BASED ON MULTIPOINT FIBER BRAGGGRATINGS FOR RESPIRATORY RATE MONITORING

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ABSTRACT

Long-term monitoring of respiratory rate (RR) is of great importance in people suffering from sleep-related breathing disorders (SBDs). Instrumented mattresses are gaining the attention of several research groups to monitor this vital sign. Among the existing sensing techniques, fiber Bragg grating sensors (FBGs) show promise in this arena. In this article, we presented a novel FBG-based smart mattress to monitor RR over time. The proposed measuring system consisted of 13 sensing elements (SEs) based on FBGs encapsulated in soft biocompatible rubber, totally embedded in multiple silicone layers. Compactness, robustness, and user comfort are the main advantages of our solution. The mattress size and the arrangement of the 13 SEs were chosen to allow monitoring subjects with different anthropometric parameters and taking up different sleeping postures. Before the overall system integration, each SE was subjected to static and dynamic metrological characterization, a process often overlooked in fiber-optic-based mattresses. Results showed a mean sensitivity to force equal to 14 pm $\cdot N^{-1}$ and a mean percentage hysteresis error always lower than 18%. The feasibility assessment of the system in RR monitoring was carried out on five healthy volunteers taking up common sleeping postures (i.e., supine -S-, right side -RS-, left side -LS-, and prone -P-) under two breathing conditions (i.e., quiet breathing -QB-, and tachypnea -T-). RR estimation showed a mean absolute error (MAE) always lower than 0.65 breaths/min. The promising findings proved the capability of our smart mattress in monitoring RR over time, encouraging the investigation of its performance in real-world scenarios.

INTRODUCTION

Sleep-related breathing disorders (SBDs) are a growing health problem worldwide and the most prevalent of all existing sleep illnesses, especially in the elderly population [1], [2].

People suffering from these pathologies complain of troublesome sleep, often characterized by snoring and prolonged obstructive apnea, resulting in a poor quality of life and, in worst cases, even in depression [3], [4]. Numerous scientific studies have also demonstrated a high incidence of cardiovascular diseases (e.g., stroke and ischemia) associated with SBDs, underscoring the severity of this issue [5], [6]. Obstructive sleep apnea syndrome (OSAS) is characterized by recurrent blockage of the upper airway leading to oxygen desaturation and awakenings in sleep [7]. Therefore, long-term monitoring of respiratory waveform and respiratory rate (hereafter RR) can be of paramount importance in the prevention and diagnosis of such diseases [8], [9].

Currently, polysomnography represents the gold standard for the investigation and evaluation of SBDs, requiring overnight patient hospitalization. It demands the placement of several sensors and electrodes on the patient's body to monitor different physiological parameters including respiratory pattern and RR [10], [11]. Nevertheless, this bulky instrumentation results in total discomfort for the patients and the potential for unreliable measurements [12]. In the last years, unobtrusive technologies are fostering increasing interest in this scenario [1]. COVID-19 pandemic has boosted the trend of unobtrusive and remote monitoring of patients' health status due to the limited access to hospital facilities [13]. The possibility of monitoring patients in an unstructured environment, without the presence of highly specialized equipment, and avoiding the placement of cumbersome instrumentation on the patient's body makes unobtrusive techniques very attractive [14]. Both contact-based and contactless technologies have been espoused in this field [15], [16], [17], [18]. Over the past decades, among the existing unobtrusive technologies, the development of instrumented mattresses for respiratory monitoring gathered the attention of several research groups and companies [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46]. In this framework, a wide range of sensing solutions have been explored including strain [21], [23], [34], [41], [42], [44], pressure [20], [22], [24], [25], [26], [28], [33

], [35], force [27], [36], capacitive sensors [37], and different types of fiber-optic-based systems [e.g., plastic optical fibers, Mach–Zender interferometers, microbend fiber-optic sensors, and fiber Bragg grating sensors (FBGs)] [29], [30], [31], [32], [38], [39], [40], [43], [45], [46]. Unfortunately, these solutions encounter some disadvantages involving several aspects, especially missing consideration of anthropometric variability among subjects in the selection of mattress size, poor sensors integrability in the measurement system, and disregard of metrological aspects at the manufacturing stage.

Out of all proposed technologies, fiber optic sensors benefit from some inherent advantages over electrical sensors for the development of instrumented mattresses.

Among others, biocompatibility, reduced size, high flexibility, inherent safety, long-term stability, humidity resistance, high sensitivity, fast response time, and, above all, immunity to electromagnetic fields. This latter feature makes optical sensors suitable in clinical scenarios since they can operate in harsh environments [e.g., magnetic resonance imaging (MRI)] without interference. On the other hand, electrical sensors typically lack all such qualities because of their low safety, high electromagnetic disturbance capacity, poor stability, easy deterioration and corrosion, and less performance, which hardly qualifies them for long-term applications. Among different types of optical sensors, FBGs are gaining momentum in a plethora of medical applications [47], [48]. Their rapid spread is warranted not only by the countless peculiarities of fiber optics, but also by their multiplexing capability allowing them to accommodate a multitude of sensors within a single fiber. Moreover, the FBG's encapsulation into silicone rubbers may increase their robustness and flexibility. In the literature, instrumented mattresses based on FBG sensors account for a small fraction of the several proposed [29], [30], [31], [46]. The presented solutions include respiratory monitoring during MRI by means of a single FBG on a plexiglass board [30], [31] and the deployment of arc-shaped pressure sensors placed directly on the bed surface [29]. A first attempt at the development of FBG-based mattresses was carried out also by our research group to investigate the feasibility of this solution for RR monitoring [46].

Here, we reported a novel smart mattress based on multiple distributed sensing elements (SEs) consisting of FBGs encapsulated in silicone rubber to measure RR over time. The original solution presents a sandwich structure made of different layers of silicone and nitrile butadiene rubbers (NBRs), ensuring robustness, compactness, and high comfortability of the device. Unlike other FBG-based solutions, our design was conceived considering the anatomical variability among subjects, allowing the instrumentation of the body portions most affected by deformations caused by breathing. Moreover, we assessed the response of each SE to force (F) in both static and dynamic conditions, a praxis often lacking in these kinds of solutions. Finally, we investigated the feasibility of the smart mattress for RR monitoring on five healthy volunteers and the influence of common sleeping postures (i.e., supine -S-, right side -RS-, left side -LS-, and prone -P-) and breathing stages (i.e., quiet breathing -QB-, and tachypnea -T-) on the performance of the proposed measuring system.

This article is structured as follows. Section II describes the FBG's working principle, the design and fabrication of the SEs, and the metrological characterization process to assess the F sensitivity values of each SE and their hysteresis error. Section III reports the design and development of the smart mattress embedding the 13 SEs and the feasibility evaluation on healthy volunteers. Finally, Sections IV and V discuss the results obtained and conclude by outlining the main remarks of our study, limitations, and future perspectives.

LITERATURE SURVEY

G. Matar, J.-M. Lina, J. Carrier and G. Kaddoum, "Unobtrusive sleep monitoring using cardiac breathing and movements activities: An exhaustive review", ***IEEE Access*****, vol. 6, pp. 45129-45152, 2018.**

At least 50% of the world's elderly population, whose range is fast growing, experience disturbed sleep. Sleep studies have become an extensive approach serving as a diagnostic tool for health-care professionals. Currently, the gold standard is polysomnography (PSG) recorded in a sleep laboratory. However, it is obtrusive, requires qualified technicians, and is time and cost expensive. With the introduction of commercial off-the-shelf technologies in the medical field, alternatives to the conventional methods have been conceived to ensure sleep stages and sleep quality detection, which may be now used at home on several nights. Cardio respiratory and physical activities abide the most promising physiological measurements to detect sleep stages without complete PSG. The statistically proven impacts and budgets related to sleep disorders are phenomenal, showing that the field needs more research. This paper aims at providing the reader with a multidimensional research perspective by presenting a review of research literature on developments made in unobtrusive sleep assessment. Additionally, a categorization of current approaches is presented based on methodological considerations, from data acquisition frameworks and physiological measurements, to information processing. Subsequently, limitations and challenges facing current solutions are discussed, and open research areas are highlighted, which we hope would pave the way for future research endeavors addressing the question: how to assess sleep stages and sleep quality less intrusively, and reliably? According to sleep research, the numbers related to sleep disorders propagation worldwide are becoming phenomenal with at least half of people over the age of 65 experience disturbed sleep [1]. This number is expected to fast grow until at least 2050 with a tendency to continue more, leading to a solid increase in sleep disorders around the world with further demanding budgets and care [2]. Researchers have shown the direct socioeconomic impact on the population and the public health [3]–[5]. Prevalence linked numbers being said, sleep disorders are a result of physiological disturbances and an inducing factor to others, making sleep a very important behaviour to explore to maintain a healthy well-being and physiological functions [6], [7]. Although the high spreading and impact of sleep disorders, a considerable reduced people's willingness to resorting to the current medical sleep evaluation is on the rise [8]. The reasons for that reduction are many, including burdensome physiological signal acquisition protocols and clinical conditions that constrain both comfort and sleep quality of the subjects, very high costs for sleep evaluation and long waiting lists before exam [9]. Therefore the need for less constrained sleep studies has given rise to a prominent research line through which researchers have been trying to propose unobtrusive alternative solutions to the conventional methods. These alternatives mainly consist of significantly reducing the large number of sensors attached on the body, and making the signal acquisition process more comfortable by targeting unobtrusively acquired signals such as breathing, cardiac and movement activities instead of obtrusive conventional measures such as electroencephalogram (EEG), electroocculogram (EOG) and electromyogram (EMG). With the application of unobtrusive sleep studies, not only comfort, costs and waiting lists are bound to improve, but also 1) this gives the option to measure sleep in ecological conditions i.e., at home, with several nights and 2) being able to reach many more people with sleep tests which gives an impactful step forward in sleep research with the collected Big Data. Several algorithms and hardware have been proposed, implemented, validated, and some of them have succeeded to reach industrial gates, thus they can be classified in two groups: industrial and academic. The concept behind these methods is to monitor a certain physiological behaviours such as physical activity, heart rate variability (HRV), breathing rate (BR) or others, and correlate its evolution with sleep stages occurrence as defined by polysomnography (PSG), or with general sleep parameters such as total sleep time (TST), or wake after sleep onset. However, due to the acquisition process induced challenges facing signal quality, either one of the proposed unobtrusive methods has succeeded to join the medico-industrial production who's typical outcome is a validated, widely used, and class-defined medical device [10], [11]. Advancements in the last decade involved in coming up with alternative solutions for an unobtrusive sleep assessment have shown that an interdisciplinary collaborative work is essential. Thus a substantial collaboration abides crucial, combining medicine with engineering to assess medical and technical constraints arising in hardware integration and signal acquisition, as well as in various levels of signal processing and data communication. Previous works have been focusing on developing unobtrusive sensing devices and hardware [12]. Thus, several sensing approaches and sensor types have been conceived and regarded as potential solutions to specific types of parameters or sleep monitoring like posture identification applications [13] and sleep/wake measurement [14]. Although the existing unobtrusive means for sleep evaluation do not provide the sufficient insight for rigorous classification of sleep cycling and sleep stage scoring, yet can give a more general and limited indications on certain important aspects of sleep such as the physical and cardiac activities during sleep. Accordingly, the need is obvious for more advancement in this field, which requires defining the challenges and opportunities paving this line of research.

N. S. Kamel and J. K. Gammack, "Insomnia in the elderly: Cause approach and treatment", ***Amer. J. Med.*****, vol. 119, no. 6, pp. 463-469, Jun. 2006.**

Poor sleep quality is a neglected clinical condition in the elderly that could predispose them to morbidities and even mortality. Several lines of clinical evidence support the potential of Meditative Movement Interventions (MMIs) in the alleviation of sleep-related disturbances in the elderly population. However, further studies are needed to provide more definitive evidence regarding the effectiveness of yoga-based MMI. The primary objective of this study is to evaluate the effectiveness of a repeated course of a yoga-based meditative intervention in a home environment to improve the sleep quality of elderly subjects. A single-case experimental design with multiple baselines will be used to assess the effectiveness of Yoga-based meditative movement as an intervention for the alleviation of poor sleep quality in the elderly. A concomitant study will also be conducted to test the effectiveness of walking as an intervention using the identical design. We will recruit 6 participants with self-rated poor sleep quality (PSQI>) with external validation using actigraphy. Each participant will be randomly allocated to a different baseline phase (i.e., 7, 10, or 14 days), which will then be followed by a daily 45-min intervention over 12 weeks. The walking group will undergo daily walking. This single-case, multiple-baseline, between-case intervention randomization design will be the first report, wherein yoga-based intervention would be longitudinally monitored for changes in the objective measure of sleep quality. Though previously considered a part of normative aging [1], progressive age-associated deteriorations in sleep quantity and quality [[2], [3], [4], [5]] have now been recognized as relevant determinants of healthy aging [6]. Neglect of these sleep-associated abnormalities could lead to age-related co-morbidities [7] spanning varied adverse health outcomes, including mood disturbances, cognitive impairment, physical effects, immune system dysfunction, and social and public health burden [6,[8], [9], [10]]. Altogether, these health ailments could ultimately affect the overall quality of life of the elderly [11]. An increased risk of mortality remains the most adverse consequence of poor sleep quality [[8], [9], [10]].

Inadequacy of sleep in older adults could be ascribed to multiple factors, including changes in circadian rhythms [12], co-morbid chronic medical conditions [12,13], and psychosocial manifestations of aging [14]. Biologically, sleep disturbance has been demonstrated to significantly affect heightened systemic inflammation, even in a general population, followed for over 5 years [15]. This association holds special clinical relevance considering that inflammaging is one of the major hallmarks of biological aging and vulnerability to age-associated diseases [16,17].

Over recent years, the rise in the aging population has led to an appreciation of the concept of healthy aging [6]. Aligning with the same, the inter-relationship between sleep and biological aging has also grabbed significant clinical attention [18]. Evidence points to an association between longevity and regularity in patterns of sleep and slow-wave sleep. Nevertheless, the oldest old individuals have been reported to exhibit strictly regular sleep patterns, evidenced by sleep diary records and actigraphy recordings [19].

Although cognitive-behavioral therapy remains the first line of recommended treatment for insomnia in the elderly, it is limited by the requirement of a large number of sessions along with economic and logistical barriers like the non-availability of clinicians to provide the therapy [20]. In this scenario, pharmacological strategies provide an easier alternative for the alleviation of sleep complaints in the elderly [21]. However, long-term use of these drugs has been associated with serious adverse health effects like developing tolerance or dependence, rebound insomnia, residual daytime sedation, cognitive impairment, and motor incoordination that pose concerns over their use [22]. Recent trends suggest increasing use of alternative interventions by the elderly such as Meditative Movement Techniques (MMIs), which fall often outside the medical system. MMIs which integrate physical activity and meditation (tai chi, qi gong, and yoga), have also been indicated to alleviate sleep problems in the elderly [11]. Compared with active therapy or usual care/wait-list controls, MMI interventions have significantly influenced sleep quality (standardized mean difference, −0.70; 95% confidence interval, −0.96 to −0.43). Given the rising popularity, comparative ready availability, and cost-effectiveness of the intervention as compared to cognitive behavioral therapy, MMIs could be a preferred choice of clinicians and therapists. However, the evidence derived from these meta-analyses remains inconclusive because of the varying studying quality and MMI modalities [11]. Yoga and meditation offer one of the most popular and promising, but under-researched MMI for sleep complaints in the elderly [23]. The mechanical explanation for yoga's beneficial influence on sleep regulation in older people is based on a number of insights. In elderly, practice of specific mindfulness-based meditations such as Vipassana, has been reported to improve their Slow Wave and Rapid Eye Movement sleep, which has been further attributed to intense brain plasticity events and modulation of the hypothalamic pituitary-adrenal (HPA) axis [[24], [25], [26]]. However, these observations have been majorly derived from cross-sectional studies. Several other studies have shown that the practice of yoga could reduce the circulating concentrations of a variety of pro-inflammatory cytokines, in particular basal TNF-α and IL-6 levels [[27], [28], [29], [30], [31]]. Further, the regular practice of yoga has also been shown to limit the level of TNF-α and IL-6 augmentation to a physical challenge of both moderate and intense exercise [31]. These pluripotent cytokines are the common biochemical denominators of sleep regulation [32,33]. The modulatory influences of yoga on lowering of inflammation markers could also be attributed to decline in sympathetic nervous system tone, and increased vagal activity [34]. Overall, Yoga's ability to modulate the levels of inflammatory markers is especially pertinent in the context of age-related changes in sleep quality, which are themselves characterized by the phenomena of inflammaging [[35], [36], [37], [38], [39], [40]]. It has also been postulated that yoga could also favorably alter circadian activity rhythms as a behavioral non-photosensitizer [41].

Effects of Mindfulness Meditation have been reported on the elderly using subjective variables, however, the outcomes studied were subjective and assessed for the shortterm [42]. As a behavioral target, sleep-based assessments need repeated measurements over shorter time intervals [43]. Recent clinical recommendations also favor a relatively longer intervention time for mind-body interventions to promote sleep quality [44]. Capturing such minute changes in sleep quality over time could be addressed using Single Case Experimental Designs (SCEDs) [45,46] with objective methods, e.g., polysomnography or actigraphy, which along with sleep diaries would be better choices [47]. Most importantly, these studies remain limited by the lack of established fidelity of the yoga-based interventions [48]. The Single-case experimental design also provides an optimal platform to overcome the limitations related to fidelity and for assessing causal relationships between interventions and outcomes [45,46]. SCED studies also aid in the visualization of more accurate functional relationships between interventions and outcomes by providing continuous feedback on the treatment progress of individual participants [49]. Polysomnography, the golden standard for sleep assessment is, however, not considered suitable for long-term studies requiring multiple assessments in a geriatric population, on account of its intrinsic, and intrusive features [50]. These features of PSG also limit its use in intensive longitudinal studies on sleep quality [51]. On the other hand, inferential methods like sleep diaries and questionnaires [51] and questionnaires like the PSQI [52], though more suitable for such long-term designs [53], and have the advantage of being relatively cheap and easy to use, may not be accurate due to the tendency in the elderly to underestimate or over-estimate sleep [47]. In such a scenario, actigraphy has been currently accepted as a valid, and practical alternative to PSG [54,55], allowing for long-term continuous sleep assessments in home settings and could be adapted to optimize sleep-related behaviors and reduce reactivity to contextual psychological stressors [56].

There remains a scarcity of high-risk population-specific research evidence on sleep interventions. Additional studies with rigorous research designs are needed to establish the efficacy of these interventions in improving sleep quality and their potential use as an intervention for various populations [57,58].

We hereby hypothesize that regular practice of yoga-based techniques of meditative movement will aid in the attainment of regularity in sleep patterns which in turn, would also align with the optimization of circulating levels of inflammatory modulators, and psychological health.

The overall aim of this work is to test the potential efficacy of a meditation-based yoga intervention to target the simultaneous alleviation of impaired sleep quality and inflammatory physiology in the elderly. This would be correlated with the study of the effectiveness of walking as an intervention, given as a cross-over intervention. We further hypothesize that expected improvements in these key mediators of health would be further reflected in their cognitive and psychological functions. This is the most significant objective of such a rigorous design and analysis where generalizability is not of great concern; rather, SCEDs are crucial when functional and causal relationships are hoped to be established with the potential for replication.

Studies reveal the effectiveness of walking as an intervention in improving the sleep quality of the elderly [59]. Walking, considered a physical activity, is easily acceptable by the elderly as it can be sustained and does not require special instructions [60]. The practice of daily walking effectively enhances sleep quality in older adults [61,62]. Therefore, it is proposed to have a single-case experimental design with between-case intervention randomization with six subjects with yoga for the first group and walking as an intervention for the second group.

D. N. Fairbanks, S. A. Mickelson and B. T. Woodson, Snoring and Obstructive Sleep Apnea, Philadelphia, PA, USA:Lippincott Williams & Wilkins, 2003.

The pathophysiologic events that lead to the loss of airway compensation in obstructive sleep apnea (OSA) are poorly understood. The development of airway instability may be secondary to changes in neurologic control, airway morphology, or both. To identify potential histopathologic features of pharyngeal tissues that may contribute to OSA, transverse sections of the distal soft palate and uvula were qualitatively compared using light and electron microscopy from 4 severe apneics (greater than 50 apnea/hour), 4 severe snorers (less than 20 apnea/hour), and 4 nonsnorers. Light microscopy of both apneics and snorers revealed mucous gland hypertrophy with ductal dilation and focal squamous metaplasia, disruption of muscle bundles by infiltrating mucous glands, focal atrophy of muscle fibers, and extensive edema of the lamina propria with vascular dilation. Severe snorers did not differ qualitatively from apneics in the characteristic changes found; however, some snorers had less extensive changes. No distinctive histopathologic findings could be associated with the development of apnea. Electron microscopy of severe apneics identified frequent focal degeneration of myelinated nerve fibers and axons. The finding of similar histopathologic changes in apneics and severe snorers supports previous speculation of a common etiology not directly related to apnea, such as vibratory trauma to pharyngeal tissues. Degenerative changes in peripheral nerves, identified on electron microscopy, however, may contribute to airway instability and the development of obstructive apnea by impairing pharyngeal reflexes. Obstructive sleep apnea (OSA) may be associated with myriad clinical consequences such as increased risk of systemic hypertension, coronary vascular disease, congestive heart failure, cerebrovascular disease, glucose intolerance, impotence, obesity, pulmonary hypertension, gastroesophageal reflux, and impaired concentration. Nonetheless, OSA remains undiagnosed in 82% of men and 93% of women with the condition. Early identification and treatment of OSA provides significant relief for individuals, prevents complications of OSA, and reduces overall health care costs. Better understanding of the pathogenesis, risk factors, diagnosis, and treatment of OSA has the potential to improve early recognition of OSA and prevention of adverse effects on the individual and society.

A. S. Baran and A. C. Richert, "Obstructive sleep apnea and depression", *CNS Spectrums*, vol. 8, no. 2, pp. 128-134, 2003.

Obstructive sleep apnea is a common sleep disorder associated with several medical conditions, increased risk of motor vehicle accidents, and overall healthcare expenditure. There is higher prevalence of depression in people with obstructive sleep apnea in both clinical and community samples. Many symptoms of depression and obstructive sleep apnea overlap causing under-diagnosis of obstructive sleep apnea in depressed patients. Sleep problems, including obstructive sleep apnea, are rarely assessed on a regular basis in patients with depressive disorders, but they may be responsible for antidepressant treatment failure. The mechanism of the relationship between obstructive sleep apnea and depression is complex and remains unclear. Though some studies suggest a mutual relationship, the relationship remains unclear. Several possible pathophysiological mechanisms could explain how obstructive sleep apnea can cause or worsen depression. Increased knowledge of the relationship between obstructive sleep apnea and depression might significantly improve diagnostic accuracy as well as treatment outcomes for both obstructive sleep apnea and depression. Obstructive sleep apnea (OSA), the most common subtype of breathing disorders of sleep, is a highly prevalent and underdiagnosed disease. The prevalence in the general population is approximately 20 percent if defined as an apnea hypopnea index (AHI) greater than five events per hour (the AHI is the number of apneas and hypopneas per hour of sleep).[1] An AHI of less than five is considered normal, 5 to 14 is mild OSA, 15 to 29 is moderate OSA, and 30 and above is severe OSA. Vulnerability to excessive daytime sleepiness (EDS) with increasing severity of AHI varies and a high AHI does not necessarily mean worsening of EDS. OSA increases the risk for poor neurocognitive performance and organ system dysfunction, due to repeated arousals and/or intermittent hypoxemia during sleep over months to years. The severity and duration of OSA necessary for development of these outcomes likely varies among individuals. In addition, there is an increased risk of mortality in patients with consequences of hypertension and cardiovascular risks, especially if their AHI is greater than 30 events per hour of sleep.

EXISTING SYSTEM

The existing landscape of sleep monitoring systems is undergoing a paradigm shift with the introduction of a Smart Mattress based on multipoint Fiber Bragg Gratings (FBG) for respiratory rate monitoring. Traditional sleep monitoring devices often rely on wearable sensors or external monitoring equipment, which can be intrusive and potentially disrupt natural sleep patterns. In contrast, the Smart Mattress incorporates

FBG sensors embedded throughout the mattress fabric, allowing for non-intrusive and continuous monitoring of respiratory rates during sleep.

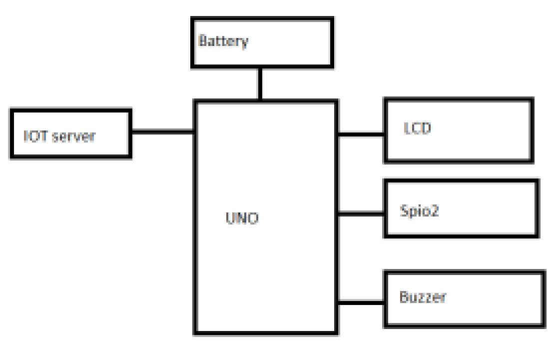
The multipoint FBG sensors, woven seamlessly into the mattress material, are designed to detect minute expansions and contractions in the chest and abdomen as an individual breathes. This innovative technology enables precise and real-time monitoring of respiratory rates without the need for any physical contact with the sleeper. The FBG sensors convert these subtle movements into measurable data, providing accurate insights into the user's breathing patterns throughout the night.

The integration of IoT connectivity further enhances the capabilities of the Smart Mattress. Respiratory rate data is transmitted wirelessly to a central hub or a companion mobile application, where users can access a comprehensive analysis of their sleep quality and respiratory health. The system can also generate alerts or notifications in case of irregularities in respiratory patterns, providing valuable information that users can share with healthcare professionals for more informed consultations.

Beyond respiratory monitoring, the Smart Mattress can offer additional features such as sleep cycle tracking, movement analysis, and environmental factors monitoring. The multipoint FBG technology allows for a holistic view of sleep health, contributing to a more comprehensive understanding of factors influencing overall well-being.

This novel approach to sleep monitoring addresses the limitations of traditional systems, offering a seamless and unobtrusive solution for individuals seeking a deeper understanding of their respiratory health and sleep patterns. The Smart Mattress based on multipoint Fiber Bragg Gratings not only represents a technological breakthrough in sleep monitoring but also holds promise for improving the early detection of respiratory issues and enhancing overall sleep quality.

IMPLEMENTATION



The proposed Smart Mattress based on Multipoint Fiber Bragg Gratings for Respiratory Rate Monitoring represents a cutting-edge solution to enhance healthcare monitoring during sleep. This innovative system leverages multipoint fiber Bragg gratings (FBGs) embedded within the mattress to accurately and non-intrusively monitor respiratory rates. The FBGs, optical sensors that respond to mechanical strain, are strategically placed to capture subtle chest and abdominal movements associated with breathing during sleep.

As an individual lies on the smart mattress, the multipoint FBGs detect minute expansions and contractions in the chest and abdominal areas, providing precise data on respiratory rates. The collected information is then processed through an integrated monitoring system that analyzes the respiratory patterns in real-time. This data can be conveniently accessed by healthcare professionals or individuals themselves through a dedicated interface, offering insights into sleep quality and respiratory health.

The non-intrusive nature of this technology makes it particularly advantageous for continuous monitoring without disrupting the user's sleep. The Smart Mattress system provides a detailed and dynamic understanding of respiratory patterns, enabling early detection of irregularities or changes that may indicate potential health issues such as sleep apnea or respiratory disorders. Moreover, the multipoint FBGs allow for a comprehensive analysis of breathing across different regions of the body, offering a more nuanced and accurate assessment compared to traditional monitoring methods.

In addition to respiratory rate monitoring, the Smart Mattress system can be integrated with other health tracking features, creating a holistic sleep monitoring solution. The application of multipoint FBGs in this context not only showcases the potential of optical sensing technologies in healthcare but also demonstrates the capability to bring advanced monitoring capabilities into the comfort of one's own home. Overall, the proposed Smart Mattress with Multipoint Fiber Bragg Gratings holds great promise for improving respiratory health monitoring during sleep, contributing to proactive and personalized healthcare management.

CONCLUSION

In conclusion, this article reports our research regarding the design, fabrication, metrological characterization, and in-lab assessment of an FBG-based mattress conceived for RR measurement. The complete integration of the 13 SEs (each encasing an FBG) within several layers of silicone material overcame the optical fiber's inherent fragility and afforded comfort to the user. Moreover, the adoption of FBG technology allowed for deploying a multisensor approach, thus monitoring subjects with different anthropometric characteristics and taking different sleeping postures. The promising findings support the suitability of the proposed system to detect RR in a wide range of applications and scenarios. Nevertheless, our study presented some limitations. The first lies in the high cost and bulky dimensions of the interrogation system necessary to enlighten the fiber and pick up the signal from FBGs. Other limitations concern the small number of recruited subjects and the in-lab validation. Therefore, future studies plan to increase the sample size to strengthen the performance analysis of the proposed solution in detecting RR and other respiratory variables. Additionally, we envisage testing smart mattress performance in real-world scenarios (i.e., home settings or hospital wards) and in-long term applications (i.e., during sleeping). In our future analyses, we intend to include benchmarking the proposed system against a reference instrument used in clinical settings (e.g., polysomnograph) and implement algorithms to detect breathing-unrelated movements and mitigate their effects on RR estimation over time.

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