A sensing platform to monitor sleep efficiency

Antonino Crivello[1] [0000−0001−7238−2181], Davide La Rosa[1], Elisabeth Wilhelm[2,3], and Filippo Palumbo[1] [0000−0001−9778−7142]

[1] Information Science and Technologies Institute (ISTI CNR), 1 Via G. Moruzzi, Pisa, 56125, Italy name.surname@isti.cnr.it

[2] Department of Health Sciences and Technology, Istitute of Robotics and Intelligent Systems, Sensory Motor Systems Lab, ETH Zurich, 8092 Zurich, Switzerland

[3] Engineering and Technology Institute Groningen, Faculty of Science and Engineering University of Groningen, Nijenborgh 4, 9747 AG Groningen The Netherlands

Abstract. Sleep plays a fundamental role in the human life. Sleep research is mainly focused on the understanding of the sleep patterns, stages and duration. An accurate sleep monitoring can detect early signs of sleep deprivation and insomnia consequentially implementing mechanisms for preventing and overcoming these problems. Recently, sleep monitoring has been achieved using wearable technologies, able to analyse also the body movements, but old people can encounter some difficulties in using and maintaining these devices. In this paper, we propose an unobtrusive sensing platform able to analyze body movements, infer sleep duration and awakenings occurred along the night, and evaluating the sleep efficiency index. To prove the feasibility of the suggested method we did a pilot trial in which several healthy users have been involved. The sensors were installed within the bed and, on each day, each user was administered with the Groningen Sleep Quality Scale questionnaire to evaluate the user's perceived sleep quality. Finally, we show potential correlation between a perceived evaluation with an objective index as the sleep efficiency.

Keywords: Sleep monitoring · Sleep quality · Unobtrusive systems

1 Introduction

Intelligent systems provide solutions to improve the health management, especially of older adults or chronically sick people, providing both short and long term monitoring. Within an aging society, interventions to preserve health, and tools to assist people, are urgently needed. It is worth noting that people experience changes, both in mental and physical aspects, especially as they grow old. As a consequence, people deal with life-changing problems. One of these problems generally affects the characteristics of the sleep habits: changes in sleep architecture, sleep duration, and quality [7]. Elderly people exhibit difficulty in falling asleep, sleep fragmentation and maintaining sleep. According to [27], sleep disturbances increases of 50% for people over 65 years old. As a conclusion, a better quality of life in elderly people may be achieved by increasing sleep quality as well as promoting good sleep [24].

In past years, several innovative systems consisting of devices for activity tracking, wearable devices and smart devices for well-being have been introduced in the market and they are daily used from a growing number of people. Sleep assessment and the related evaluation research has grown steadily [25, 14] as well. An important aspect to consider is that despite younger people's perceptions, seniors' use of technology is the rule rather than the exception. As reported in [18], seniors (aged 65 to 75) report an average of 19 to 31 interactions per day with their daily appliance, including computers and devices. Elderly users are considered less inclined to accept new technology than younger people. Typically, if they are motivated to use new technological solutions – because the benefits are clearly perceived – this inclination changes. As a consequence, in order to increase the acceptability, devices equipped with long-life batteries or, in general, devices easy to install and which require low effort for maintaining and interacting have been proposed. The system proposed in this paper is composed by several force-sensing resistor placed as a grid between the mattress and the slats. It can be easily deployed in a home setting and, most important, according to the motivations introduced above, performs its evaluation in an unobtrusive way. The scope of the proposed system is monitoring the sleep in order to evaluate the sleep efficiency (SE). In fact, SE is commonly defined as the ratio of total sleep time (TST) to time in bed (TIB) and it plays a fundamental role in sleep research [20, 16]. We have deployed our system in a real world setting within a bigger sleep study held at the ETH, Zurich. Finally, we compared the objective measurements performed by the proposed system with the Groningen Sleep Quality Scale (GSQS) questionnaires to evaluate the correlation between the objective SE index and the perceived sleep quality collected through the questionnaires.

2 Related work

An accurate sleep monitoring is fundamental in order to detect early signs of sleep deprivation and insomnia, evaluating sleeping habits, and consequentially implementing mechanisms and systems for preventing and overcoming sleep problems [10].

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 [12]. For the purpose of the sleep monitoring, the body movements are analyzed not only to infer when a subject is resting or not, but also to measure some sleep variables like: total sleep time, bedtime and rise time [11]. In order to record sleep sessions on an extended period in a home setting more efforts should be spent to find reliable sleep monitoring system able to monitor the human sleep and its characteristics.

Fortunately, technological advances have allowed the development of non-invasive, long-life, battery powered, wearable devices equipped with tri-axial accelerometers (i.e., actigraphy) able to monitor and collect data generated by movements. Some devices exploit a piezo–electric mechanism to detect movements, along two or three axes, and to digitally count the accumulated movements across pre–designed epoch intervals (e.g. 1 min), storing them in an internal memory.

Wearable devices for actigraphy, and in particular wrist-worn actigraphy devices measuring sleep parameters [2] have been validated through the comparison with polysomnograpghy which is considered the gold-standard method [14, 15]. In general, longer actigraphy-based monitoring may correlate better with gold-standard method. The strengths of actigraphy-based systems are the low impact on maintaining for the users and their low cost. However, the major weakness of this method is the limitation in distinguishing activity from motionless while users are awake or being asleep.

Despite the main strength of actigraphy lies in the ability of monitoring sleep behaviour and inferring sleep wake patterns over long periods of time at home, actigraphy also has several weaknesses. In [1], the authors report that up to 28% of weekly recordings of children and adolescents were insufficient for the sleep analysis. The main reasons for data loss included patient non-compliance to the pre-defined protocol (inability to complete the diary or log and misplacement of the wearable actigraph device), illness, and technical problems. In [3, 19], the use of wearable general purpose sensor technologies to monitor the bed posture of patients is proposed. In order to overcome the issues related to wearable devices, no contact systems based on several technologies (e.g. camera, accelerometers) have recently been proposed. For example, in [23], an unobtrusive system able to infer the bed posture and the breathing signal is presented. The system is based on an expensive technology which employs a sensor, called Kinotex, that was developed by the Canadian Space Agency for tactile robotic sensing. Finally, in [21], an inexpensive system based on placing above the mattress a capacity textile sensing technology is described. However, the authors noticed problems on the reproducibility of the experiments, due to the movement of the textile system, which necessitates a new calibration phase each time.

Another technique to assess sleep quality, exploiting sensors or pads installed under the mattress, is the ballistocardiography (BCG). It is based on the detection of the ballistic forces of the body generated by the pumping of the blood into the circulatory system with each heartbeat and breathing cycles. The forces generated by the human body are used to detect the heart rate, heart rate variability and respiratory rate. Commercial devices based on this principle use both pneumatic pressure sensors (e.g. Withings Sleep Analyzer) or piezoelectic sensors(e.g. TE Sleep Monitoring, Beautyrest Sleeptracker) to detect the movements produced by the body. Although BCG allows to use minimally invasive devices, it has some disadvantages such as potential inaccuracies while measuring the physiological parameters when two or more subjects are on the same bed, sensitivity reduction due to the bed sheet or blankets and subjectivity of the involved biological markers [5].

The system proposed in this paper is able to merge the inexpensive feature of [23] and the unobtrusive feature of [21], just placing, under the mattress, several FSR, able to report the force pressure generated by the patient over the mattress.

3 The proposed sensing platform

Taking into account both the findings described in the previous section and our former work in this field described in [4, 6, 9, 8], we present an improved version of the sleep monitoring system able to generate a synthetic sleep quality index representing the user's night resting capacity. The system can be easily deployed in every home setting and could also be integrated in wider Ambient Assisted Living scenarios, running side by side with other user's monitoring platforms to provide multidomain continuous monitoring (e.g. stress analysis, physical exercise, social activity). Thanks to its extremely low intrusiveness, the system can also be deployed in environments involving older people with sleep impairments.

Our system relies on force-sensing resistors (FSRs), arranged in a grid pattern, placed between the mattress and the slats (Figure 1).

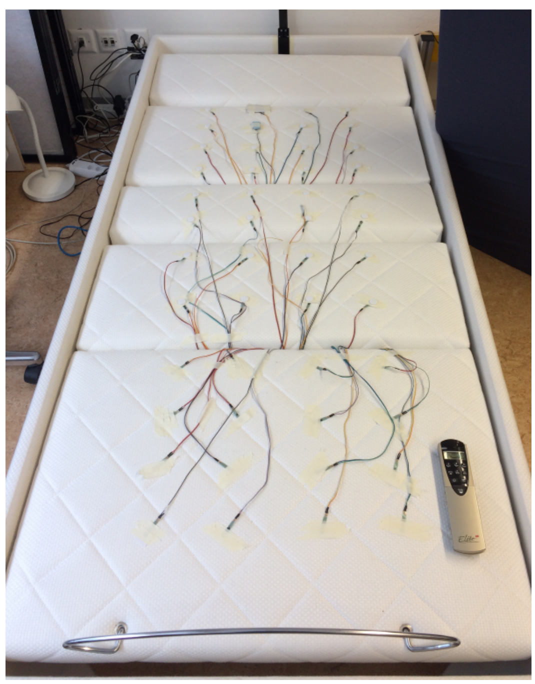

Fig. 1: The proposed system deployed on the mechanical bed.

These sensors consist of a conductive polymer which changes its electrical resistance proportionally with the force applied on the sensor surface. In addition, the sensors are characterized by an extremely low profile (less than 0.5 mm), low cost, a good shock resistance and a low temperature sensitivity with an output variance up to 0.36% per degree C. We use these sensors to detect the distribution of the pressure exerted by the human body lying on the bed. In order to acquire and store the pressure values over time, the sensors are connected to a Raspberry Pi single-board computer by means of analog-to-digital converter units which translates the electrical voltage coming from the sensors to a digital format.

The Raspberry Pi board is able to continuously collect raw pressure data while recording it on permanent storage. At the end of a sleep monitoring session, the logs, stored in a CSV format, can be retrieved and further analysed. By exploiting the network connection, multiple boards can be combined together to increase the amount of sensing points or integrated with other sleep or environmental monitoring devices to provide automatic data collection and aggregation. From the raw data, consisting in the pressure readings generated by the sensors over time, our algorithm evaluates the frequency and the number of body movements performed by the human body during the night. In particular, we first perform a preprocessing phase by: (i) computing the total pressure exerted by the body over time and (ii) applying a moving window average to the data in order to reduce the impact of the environmental vibrations and the electrical noise which are mixed up in the signals. Furthermore, we apply an hysteresis thresholding in order to strengthen the detection of the user on the bed. The upper and lower threshold values are customized for each user to match their weight footprints in order to separate the sensor readings matching the empty bed from those matching the loaded bed (Figure 2).

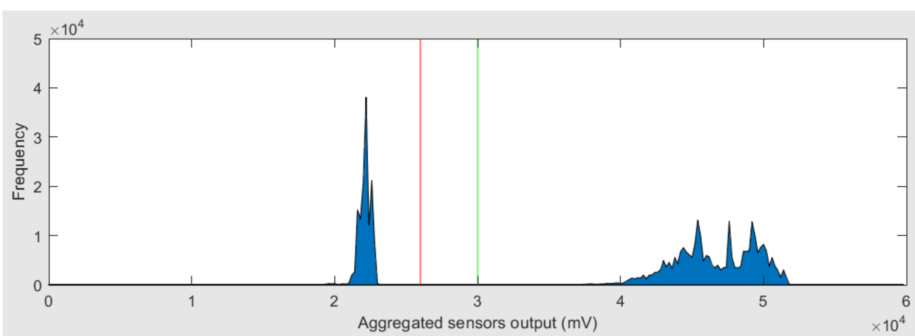

Fig. 2: Distribution of the pressure values used to determine the lower (red) and upper (green) hysteresis thresholds to detect the user presence on the bed.

Besides, to detect the user movements, we compute the amount of variation of the pressure values within a fixed-size moving window; we consider a movement

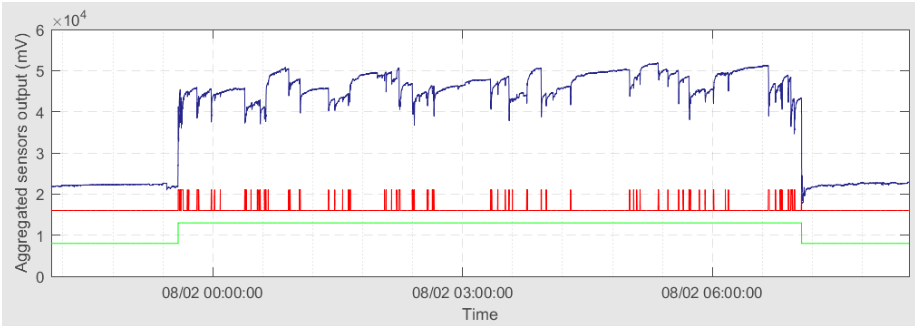

Fig. 3: Detection of the user presence on the bed (green) and his movements (red) based on the total pressure over time (blue).

whenever this quantity exceeds a given value, calibrated for each user. Taking into account both the user presence on the bed and the sequence and duration of the user movements, the algorithm produces a synthetic index, namely Sleep Efficiency index. The index, based on the findings in [5], takes into account the number and the duration of the movement periods during which the user is assumed to be awake, the time taken to sleep as well as the total time spent in bed [22]. In the first place, in order to compute the sleep efficiency index, the following parameters are derived from the pre-processed data:

- Time In Bed (TIB): time elapsed between the first instant the user went on the bed in the evening and the last instant the user got out of bed in the morning; this parameter might include periods during which the user get off the bed during the night
- Sleep Onset Latency (SOL): time elapsed between the first instant the user went on the bed in the evening and the instant the user is assumed to sleep (no movements detected within a fixed time window)
- Wakefulness After Sleep Onset ($WASO$): time the user is assumed awake, i.e. the periods of time during which the user is moving plus the periods of time the user got out of the bed during the night

From these parameters, the Total Sleep Time (TST) is computed as in equation 1.

$$TST = TIB - WASO - SOL \tag{1}$$

Eventually, the Sleep Efficiency index is obtained through the formula in equation 2.

$$SE = \left(\frac{TST}{TIB}\right) \times 100 \tag{2}$$

4 Preliminary analysis and discussion

To prove the feasibility of the suggested method we did a pilot trial within a bigger sleep study [26]. The study protocol was approved by the Ethics Committee of ETH Zurich, no. EK 2015-N-70 and retrospectively registered at https://clinicaltrials.gov, no. NCT04053738. Written informed consent was obtained from all subjects.

Five male participants (age: 25.8 SD: 4.5 years, body mass index: 22.4 SD 2.3 kg/m2, Epworth sleepiness scale (ESS) at baseline 6.3 SD: 2.3) out of the group of subjects that were recruited in 2017 were selected for this pre-trial. This subgroup included one participant with an EES above 10 which indicates excessive daytime sleepiness [13].

The sensors were installed within the bed for all four nights. On each day, each user was administered with the Groningen Sleep Quality Scale (GSQS) questionnaire [17] to evaluate the user's perceived sleep quality.

Table 1: Comparison between users' GSQS scores and the SE indexes. Darker and lighter blue in GSQS and SE columns represents the scores and indexes obtained during the nights with and without the bed moving, respectively.

User	GSQS Score	Sleep Efficiency Index	Intraclass correlation	GSQS Score σ^2	GSQS Score σ
1	8	34	-0.98	4.67	2.16
	7	42			
	6	62			
	3	83			
2	3	78	0.26	0.92	0.96
	4	62			
	5	86			
	3	76			
3	4	77	-0.67	3.0	1.73
	0	84			
	1	86			
	1	78			
4	2	96	-0.36	1.0	1.0
	2	97			
	2	83			
	0	97			
5	2	83	-0.06	0.33	0.58
	1	86			
	2	93			
	1	91			

Table 1 shows the GSQS scores (low values indicate a better perceived sleep quality and viceversa) and the SE indexes obtained for each user (the higher the value, the better the computed sleep efficiency). We use the negative intraclass correlation (ICC) as a descriptive statistic to quantitatively measure the correlation between the output of our system and the answers of the same user to the GSQS questionnaire for the four nights. Negative correlation or inverse correlation is a relationship between two variables whereby they move in opposite directions. The degree to which one variable moves in relation to the other is measured by a negative correlation coefficient, which quantifies the strength of the correlation between two variables. The higher the negative correlation between two variables, the closer the correlation coefficient will be to the value -1. We used it to describe how strongly our index represents the perceived sleep quality for the same user in their group of nights (ICC close to -1 in presence of high correlation and close to 0 or positive values with low or very low correlation). We also show the variance σ^2 and standard deviation σ of the GSQS scores for each group of nights in order to detect the subjective range of possible answers to the questionnaire. Low standard deviation means data are clustered around the mean, while high standard deviation indicates data are more spread out. We believe that groups of nights with high standard deviation in their GSQS score emphasize more the "good" and "bad" nights in terms of sleep quality. We observed that the performance of our systems improves in users showing higher variance in their perceived sleep quality, i.e. having one or more particularly good or bad nights. For user 1, we obtain an intraclass correlation of -0.98, with the user showing a high variance in their GSQS scores. For user 2, instead, we obtained a very low correlation with a positive ICC value, with the user showing a very low variance in their GSQS scores due to very similar nights in terms of perceived sleep quality. This can lead to further investigation of the proposed system as sensitivity measure when used to detect anomalies in the monitored nights related to possible sleep pathologies/diseases.

During the study, in two out of the four nights, interventions in the form of bed movements were provided. Since these interventions could influence our analysis we analyzed the data once considering all nights and once considering only the nights in which the bed did not move. In Table 1, we indicated with darker blue the scores and indexes obtained during the nights with the bed moving, while with lighter blue the ones obtained during nights with no movements of the bed. We observed that the system is robust to this kind of external mechanical perturbations, showing almost the same correlations: overall $r = -0.84$; correlation between nights and GSQS score with the bed moving $r = -0.87$; correlation between nights and GSQS score without the bed moving $r = -0.86$.

For the sake of completeness, we put together all the SE indexes obtained for all the users. This can be useful to see how the proposed system performs without tuning the parameters to the subjective perception of sleep quality of a particular user. The obtained results are shown in the correlation chart in Figure 4. It shows the regression of the SE indexes over the GSQS scores. The coefficient of determination R^2 provides a measure of how well observed outcomes in terms of GSQS scores are replicated by the proposed system in terms of SE indexes, based on the proportion of the total variations. We obtained a good fitting model with $R^2 = 0.708$ and a low deviation between nights with the bed

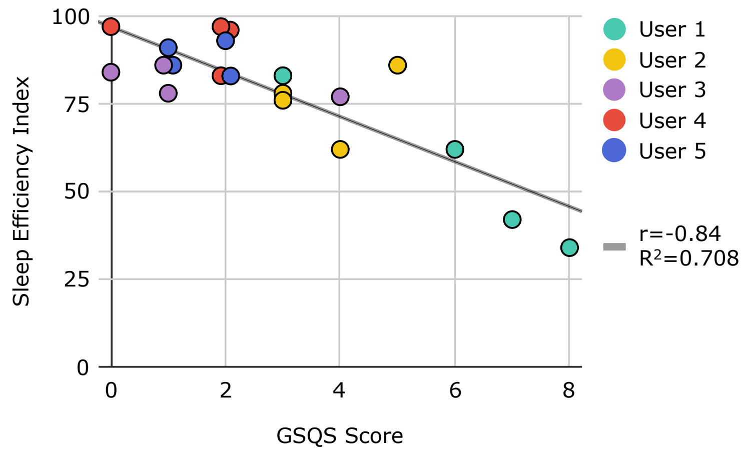

Fig. 4: Correlation chart and regression analysis.

moving, obtaining $R^2 = 0.74$, and not moving, obtaining $R^2 = 0.76$ (these values are not shown in the figure for a better visualization of the overall performance).

We can conclude that in this pilot trial we were able to show that there is a general correlation between the subjective GSQS and the sleep efficiency index derived with our FSR sensor setup. In the future we will have to show whether we can also find a good correlation to the gold standard polysomnography. Furthermore, it would be interesting to use the system in specific scenarios, like older adults with sleep problems in ambient assisted living environments.

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