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Sleep comfort analysis using a part-based mixture model with nighttime infrared video

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ABSTRACT

This work investigated a new challenging problem: how to analyze human sleep comfort which is an urgent problem in intelligent home and medical supervision, especially in intelligent temperature control of air conditioners. To overcome this problem, a novel part-based mixture model is proposed to estimate human sleep comfort. Unlike conventional human sleep comfort analysis using uncomfortable and expensive wearable-device, a remote infrared camera and a cheap temperature sensor are used to collect human sleep posture and real-time temperature information. Moreover, a robust sleep posture feature extraction method is firstly proposed to describe sleep comfort not matter human body is covered by a sheet or not. Experiments on a custom-made database demonstrated that the proposed method has promising performance for on-line human sleep comfort analysis.

1. Introduction

Sleep is a complex behavioral state that occupies one-third of the human life span [1]. Sleep quality is of fundamental importance to human health. Sleep gives your body a rest and allows it to prepare for the next day. It's like giving your body a mini-vacation. Sleep also gives your brain a chance to sort things out. It is important for a wide variety of applications to be able to analyze sleep comfort and sequentially improve sleep quality, especially in intelligent home and medical supervision.

Ambient temperature is a crucial factor for sleep quality. People may wake up when the ambient temperature is too high or too low. Air conditioner is widely used to control the ambient temperature in our daily life. However, different sleep stages require different ambient temperatures [2], and current automatic intelligent air conditioner can only achieve thermostatic control which cannot meet the demands of different sleep stages and would inevitable affect sleep quality.

To overcome this problem, this work proposes a novel sleep comfort analysis method that is used to analyze sleep posture and measure the current comfortable levels of sleep based on real-time inputs from infrared video and a temperature transducer. Our research is very useful for current intelligent air conditioner technology which is limited to thermostatic control. The intelligent air conditioner assisted by our method can adaptively control the ambient temperature based on real-time sleep comfort measurement result and consequently improve sleep quality.

The remainder of the paper is organized as follows. Section 2 introduces related works of sleep comfort analysis and discusses the contributions of the paper. In Section 3, the description of different sleep thermal comfort categories and the proposed approach are presented. Experimental results and discussions are given in Section 4. Section 5 gives a conclusion of this paper.

2. Related works

There has been several works on sleep quality analysis or sleep comfort analysis [3–8]. Some sleep analysis techniques using inertial sensors which including polysomnographic measurements, accelerometers, gyroscopes, and magnetometers have been developed for doing this [9–12]. Pedro et al. [9] applied an intelligent system to classify sleep stages using electrophysiological signals which are recorded by sticking silver-disk electrodes to the skin or to the scalp. Kishimoto et al. [10] proposed a technique to estimate sleeping postures from data acquired using a tri-axis accelerometer strapped to subject's chest. Gautam et al. [11] introduced an algorithm to detect sleep using a smart phone with the help of its in built accelerometer sensor. However, these sensors need to be attached to human body, which causes inconvenience during sleep and consequently decrease sleep quality. Recently, the approach of dispersed sensors embedded in the mattress has become promising. The sensors embedded mattress can record the pressure distribution of human bodies, which forms a pressure image.

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Merilahti et al. [3] compared different measures for total sleep time and sleep quality. They analyzed visually long-term sleep data collected with actigraphy, sleep logs and ambient sensors to gain more reliable results and compared these results to each single method's output. Liu et al. [13] collected and analyzed the data of volunteers' nightmare so that the corresponding strategy and the simulating model of fuzzy control are established after careful analysis for monitoring sleep quality. However, these methods for sleep posture recognition are based on local features and individualized pre-training, which requires considerable efforts to apply in a large population.

Compared with above mentioned wearable or contact-based sensors, video cameras [14] and infrared cameras [15] are more suitable for sleep analysis because these sensing modalities are unobtrusive to users and minimize the privacy concerns. They can remotely detect global human sleep posture without attaching to the human body. Heinrich et al. [14] proposed a camera-based system combining video motion detection, motion estimation, and texture analysis with machine learning for sleep analysis. The system is robust to time-varying illumination conditions while using standard camera and infrared illumination hardware. Fan et al. [16] developed a home sleep screening technique with the aim of assisting the evaluation of quality of sleep in smart TV environment using day-and-night video cameras. However, the performance of existing cameras-based approaches are not satisfied because they suffer from image noise due to low visibility at night and lacks an effective sleep posture descriptor or model used to estimate human sleep comfort.

Besides the selection of sleeping sensors, sleep analysis methods are also of greatest importance for sleep quality or comfort works which include sleep feature representation and sleep feature classification. Most of sleep studies [17–19] apply polysomnographic (PSG) measurements to describe sleep features, composed of electroenphalogram (EEG), electromyogram (EMG), and electrooculogram (EOG) readings. Then a feature selection or feature transformation methods are generally used to remove artefacts that corrupt the information content and reduce the effectiveness of the classification and recognition tasks. Powerful classification approaches such as hidden Markov model (HMM), support vector machines(SVMs), back propagation (BP) network and adaptive boosting (AdaBoost) are finally used to improve classification or analysis performance. Although polysomnography is accurate recordings physiological signals of human, sleep related information does not dominate principle components in polysomnography signals which are composed of waves that have different frequency bands. It is difficult to find an effective feature selection method to select meaningful information from polysomnography signals because it is similar with black box. Even an powerful classifier could not improve the classification performance since the sleep features are widely polluted by irrelevant information.

In recent years, image-based approaches utilizing video to investigate sleep quality or comfort have become promising [14,15,20,21]. Heinrich et al. [20] studied body movements during sleeping by clustering similar motion vectors in different body parts. Liao et al. [21] adopted the motion history image (MHI) approach to infer motion information and estimate sleep status from the acquired video. However, traditional image-based sleep analysis approaches are mainly based on dynamic sleep features and rarely consider obscuration of the bodies edges by the cover. Human body is generally static during most of sleeping time and its subtle chest or abdomen movements causing by breathing are difficult to extract due to the image noise and low visibility at night. Therefore, image-based approaches reported in the literature on sleep quality or comfort analysis are rather limited.

The problem of human sleep comfort analysis is closely related to that of sleep posture analysis and human motion analysis because most of sleep quality or comfort work are based on sleep posture analysis or derive from human motion analysis methods [22–29,29–37]. Xu et al. [38] proposed a novel body-Earth movers distance (BEMD) for seven sleep postures recognition with a pressure sensitive bedsheet. Liu et al. [29] developed a novel framework for pressure image analysis to monitor sleep postures, including a set of geometrical features for sleep posture characterization and three sparse classifiers for 6 common postures recognition. Nakajima et al. [27] developed a real time system of image sequence analysis to evaluate both a subject's posture changes and respiration in bed. Two sleep apnea syndrome patients who had not been diagnosed before the test was found. However, most of existing sleep posture techniques developed so far are studied for medical diagnosed and sleep disease treatment which apparently are not suitable for sleep comfort analysis.

In our literature review, we found that the challenges of sleep comfort analysis are to develop an effective way to well describe or extract sleep comfort features even human body is fully or partially covered and unobtrusively acquire sleep data without taking the privacy concerns, while existing sleep quality or comfort studies mostly focus on using powerful classification methods to analyze noisy sleep features and rarely investigate covered body problem.

In this work, a new challenging problem that analyzing human sleep comfort in current ambient temperature environment is investigated. To the best of our knowledge, none of the existing works on sleep analysis attempt to estimate sleep thermal comfort. The contributions of this paper can be summarized as follows. First of all, unlike conventional human sleep comfort analysis using uncomfortable and expensive wearable-device, a remote infrared camera and a cheap temperature sensor are used to collect human sleep posture and real-time temperature information. Secondly, the categories of sleep thermal comfort are defined and a detailed sleep comfort features description is given based on numerous experiment analyses. Thirdly, a part-based mixture model based on a sleep posture feature descriptor is firstly proposed to estimate sleep comfort not matter human body is covered by a sheet or not. The novelty of the proposed part-based mixture model is found in establishing a suitable sleep thermal comfort model based on human posture and current ambient temperature. Moreover, the novel sleep posture feature descriptor is proposed based on sufficient sleep data analysis and experimental results demonstrated that the proposed method has promising performance for sleep thermal estimation.

3. Proposed method

Because ambient temperature is a crucial factor for sleep quality, this work focuses on evaluating thermal comfort of nighttime sleep. Compared to other sleep information sensors, infrared camera collects relatively detailed sleep posture information in nighttime. Moreover, in order to expand our research into further applications such as sleep temperature control of intelligent air conditioner, a temperature transducer is also used to measure current ambient temperature which makes the mixture sleep comfort model more exact.

3.1. Sleep thermal comfort category

Before evaluating sleep comfort levels, the categories of sleep thermal comfort should be defined. Actually, sleep thermal comfort analysis is a new challenge problem and there has not been an available work on it so far. In order define the levels sleep of sleep comfort, 120 sequences of sleep video in real situation is collected to analyze the sleep thermal comfort categories. Some frames of sleep video are shown in Table 1.

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