Wearable-Triggered Smart Home Temperature Automation System to Promote Sleep Quality

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***Abstract*—This paper presents a novel study that explores the use of individual sleep data from wearables to optimize home thermal environments and sleep quality.**

Keywords—wearable, sleep quality, smart home, temperature

I. Introduction

Approximately 50 to 70 million Americans suffer from sleep disorders, and one in three adults (about 84 million) do not regularly achieve the recommended amount of uninterrupted sleep. [1] While patients may suffer from both sleep disorders (e.g., sleep apnea, insomnia, restless legs syndrome) and chronic medical conditions (e.g., depression, anxiety, chronic pain), sleep deprivation is also prevalent among healthy individuals with no known medical conditions. Poor sleep quality can stem from various causes such as stress, sleep hygiene, diet (caffeine/alcohol intake), physical activity levels, and environmental factors. [2] A 2012 study identified room temperature as a critical factor in achieving quality sleep. Excessively high or low ambient temperatures may affect sleep even in individuals without insomnia. [3]

Bedding and room temperature can be adjusted during the night; however, these adjustments often need to be made while individuals are awake, contributing to more awakenings, which is one indicator of bad sleep quality. While many studies have explored the correlation between the thermal environment and sleep quality, few have focused on interventions.

Smart home automation systems are increasingly being used to optimize life quality. However, few of them use health data as input for automation. Wearables mainly collect data but do not make interventions.

This project highlights the potential to enhance sleep quality by optimizing home thermal environments tailored to individual needs. It will be a novel study using wearable data to make interventions to improve sleep quality.

Our experiment collected individual sleep data to verify the correlation between ambient temperature and sleep quality, using an Inertial Measurement Unit (IMU) and thermostat sensor on our microcontroller to measure sleep restlessness and ambient temperature, respectively, while controlling for potential confounders and covariates.

Our initial findings indicate a potential correlation between increased restless movement and higher temperatures, highlighting specific temperature thresholds linked to decreased movement. These observations suggest the potential development of an automated temperature regulation system using individual historical IMU data. By leveraging past data, this system could determine the optimal temperature associated with reduced restlessness, facilitating presetting of air conditioning temperatures or dynamic adjustments during sleep based on observed movements.

We also contributed a dataset of IMU movement during sleep, which can be used for further research.

II. Related work

A. Sleep Quality

Defined as an individual's satisfaction with all aspects of the sleep experience, sleep quality encompasses four key attributes: sleep efficiency, sleep latency, sleep duration, and wake after sleep onset. [4] Sleep efficiency is calculated by dividing total sleep time by total time in bed, which includes time spent in non-sleep-related activities such as reading or watching television before sleep and after waking. Sleep latency refers to the time it takes to fall asleep after "lights out." Sleep duration measures the total time spent sleeping. [5] Wake after sleep onset refers to periods of wakefulness occurring after defined sleep onset. Sitting up or leaving the bed can be considered awakening, while constant tossing and turning to get settled and comfortable can be classified as abnormal restlessness during sleep. [6] [7]

To summarize, good sleep quality means longer total sleep time, shorter time to fall asleep after lights out, and fewer awakenings. In this study, we will use fewer restless movements as an indicator of good sleep quality.

B. Influence of Ambient Temperature

Studies have shown that room temperature significantly influences sleep quality. Optimal sleep generally occurs in environments where the temperature is between 60 to 67 degrees Fahrenheit. [8] Both high and low temperatures can disrupt sleep by causing the body to work harder to regulate its temperature, either by cooling down or generating heat. [9, 10] A bedroom temperature that is either too cold or too hot can make it harder to stay asleep. [11]

C. Adjusting Ambient Temperature

In the past, several experiments have been conducted to adjust ambient temperature to improve the sleep quality of specific populations, such as those in nursing homes. [12] However, these systems are generally not driven by individual data. Finding the ideal sleep temperature is subjective and can vary from person to person.

D. Limitations of Existing Wearables and Smart Home Products

Current wearables, such as Apple Watch and Garmin Watch, only collect data but do not make interventions. Smart home products, such as Apple HomeKit, Google Assistant, and Amazon Alexa, allow users to schedule temperature settings for the air conditioner. However, many users lack the knowledge to effectively adjust the temperature to suit their sleep needs and the literacy to conduct self-experiments to figure out the triggers for their problems. [13]

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While data-driven smart home devices like the Nest Learning Thermostat and Ecobee Smart Thermostat automatically adjust the temperature, their primary focus remains on enhancing energy efficiency, cutting electricity bills, and improving convenience based on user schedules[14]. Importantly, they do not utilize individual health data as input for their predictions. To date, there has been limited research on smart home automation that utilizes the owner's physiological state. The most relevant research explores the possibility of using EEG (electroencephalography) signals to control household appliances. [15]

III. METHODS AND RESULT PRESENTATION

This experiment will involve one healthy individual over two days, with ambient temperatures set at an average of 82°F natural temperature on the first day and 65°F on the second day using air conditioning. The analysis will include both same-day and day-to-day comparisons. We will control for potential confounders such as stress levels, physical activity, and screen time by conducting the experiments on weekends, ensuring consistent bedtime (2:19 am), maintaining the same caffeine and no alcohol intake, using the same room to control for environmental noise, and keeping clothing and bedding consistent across the experiment days. The goal of this experiment is to verify the correlation between ambient temperature and restlessness during the night, and identify the temperature at which the participant experiences the least awakenings or fewer frequent movements.

A. *Data Collection*

Ambient temperature is measured by the thermostat on the microprocessor, sampled at a rate of 100 Hz. The temperature is calibrated before the experiments to ensure consistency with the temperature measured on the wrist. The calibration method involves the participant wearing the board on the wrist for 30 seconds and then placing it on the nightstand for 30 seconds to verify consistent readings. However, in future designs, it would be preferable for the thermostat functionality to be separate from the IMU wristband to prevent interference from bedding. Body movement data is measured by the IMU at a sampling rate of 100 Hz.

B. *Devices, Wearing Positions, and Sensing Modalities*

- Devices: IMU, Seeed nRF52840, Seeed nRF52840 Extension board, LiPo 3.7V 500mAh battery (JST connector)
- Wearing Position: The board is attached to a wristband.

Fig. 1(a). Device on the wrist

We choose to wear the device on the wrist for the following reasons:

Fig. 1(b). Wearing the device during sleep

I. This location is useful for detecting overall body movements and frequent position changes during sleep, which can indicate restlessness.
II. It is the most comfortable position without disrupting sleep.
III. It is highly likely that the sensor will stay in place throughout the night.

A. *Definition of Restlessness*

When experiencing good sleep quality, people are generally less active and have fewer movements, but they are not completely static. Therefore, to differentiate normal sleep movements from restlessness, we define three major movements as indicators of restlessness during the night: sitting up, leaving the bed, and constant turning and tossing. We perform these activities for 30 seconds each and collect IMU data to define the magnitude threshold.

Fig. 2(a). Sitting Up

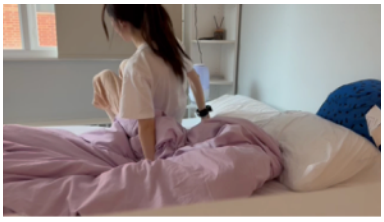

Fig. 2(b). Leaving the bed

Fig. 2(c). Turning and Tossing

Identify applicable funding agency here. If none, delete this text box.

B. *Data Preprocessing*

First, we aggregate the data in 1-second intervals. Second, since we are only concerned with the magnitude and number of movements, we compute the L2 norm of both the accelerometer and gyroscope data to determine the magnitude of movement..

$$\text{L2\_norm\_accel} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

$$\text{L2\_norm\_gyro} = \sqrt{g_x^2 + g_y^2 + g_z^2}$$

As these measurements are on different scales, we scale them and create a combined movement metric by computing the L2 norm of both the scaled accelerometer and gyroscope data.

$$\text{Scaled\_L2\_norm\_accel} = \frac{\text{L2\_norm\_accel} - \min(\text{L2\_norm\_accel})}{\max(\text{L2\_norm\_accel}) - \min(\text{L2\_norm\_accel})}$$

$$\text{Scaled\_L2\_norm\_gyro} = \frac{\text{L2\_norm\_gyro} - \min(\text{L2\_norm\_gyro})}{\max(\text{L2\_norm\_gyro}) - \min(\text{L2\_norm\_gyro})}$$

$$\text{Combined\_Scaled\_L2\_norm} = \sqrt{(\text{Scaled\_L2\_norm\_accel})^2 + (\text{Scaled\_L2\_norm\_gyro})^2}$$

IV. EXPERIMENT RESULTS

A. *Correlation Analysis*

Overall, the trend line indicates that as the temperature increases, the magnitude of the movement generally becomes larger, peaking at 83°F, and then gradually decreases beyond this point.

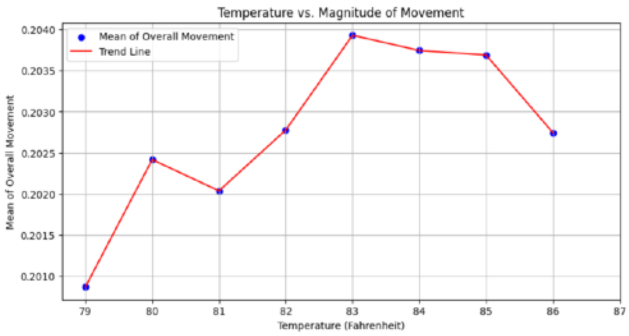

Fig. 3. Temperature vs. Magnitude of Movement

This correlation can be further supported by subsequent correlation analysis. While the Pearson correlation between temperature and movement is only 0.16 with a p-value of 0, the Spearman correlation between temperature and magnitude of movement is 0.6, indicating a strong correlation. This suggests a non-linear relationship between temperature and movement, indicating that individuals tend to make more movements as temperature increases.

When we conduct day-to-day analysis and compare the results of the first day, with an average temperature of 82°F, to the second day, with a constant temperature of 65°F, we observe that there is no restless movement on the second day. This may suggest that the subject has better sleep quality at lower temperatures.

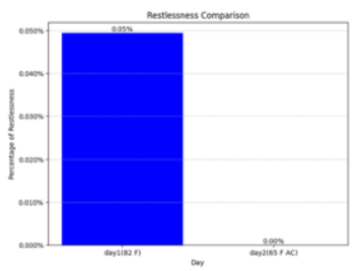

Fig. 4. Day-to-Day Restlessness Comparison

However, since the data and analysis are based on a single case, more lab-based experiments with additional participants need to be conducted to make the conclusion more robust.

B. *Optimal Temperature Identification*

Temperature with the Most/Least Movement: Based on the restless movement threshold defined by the three movements below, we compute the number of restless movements during the whole night in each temperature bin. The graphs show that the participant experiences restless movements or awakenings at 82°F, 83°F, and 85°F, suggesting discomfort at these temperatures.

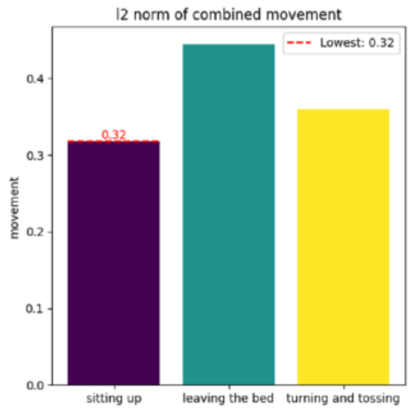

Fig. 5(a). Movement Threshold for Restless Movement

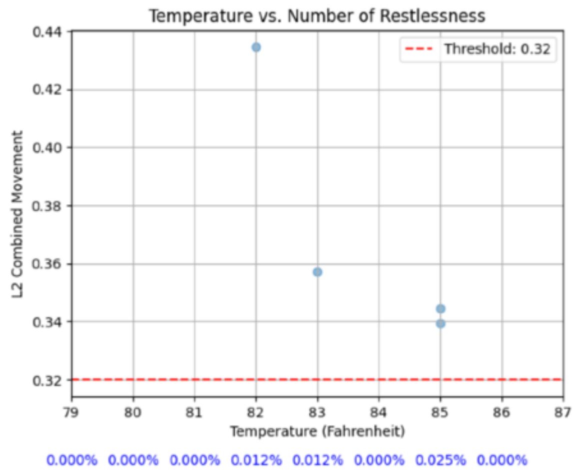

Fig. 5(b). Temperature vs. Number of Restlessness

V. CONCLUSION AND DISCUSSION

Our preliminary findings suggest that restless movement may increase with rising temperatures, with specific temperatures associated with reduced movement. These observations support the feasibility of designing an automated temperature control system based on individual historical IMU data. By analyzing historical data, the system could identify the optimal temperature at which an individual tends to be less restless. This technology could be utilized to pre-set air conditioning temperatures before sleep or to dynamically adjust temperatures during sleep in response to observed restless movements.

However, our conclusions require further validation through expanded experimentation. The impact of temperature variations on sleep quality needs further study; future experiments should maintain constant temperature conditions to isolate the effect of temperature variation on restlessness.

Additionally, it is crucial to consider the internal sleep cycles in our studies. Human sleep involves multiple stages, each with distinct physiological and neurological characteristics. Particularly during deep sleep stages, individuals exhibit reduced physiological responsiveness, suggesting that ambient temperature changes may have a diminished effect on sleep quality during these periods. Therefore, understanding the distribution of sleep stages in conjunction with temperature variability could provide more nuanced insights into how and when temperature adjustments might be most beneficial. The sleep stage can also act as a confounding factor, and it's essential to compare the correlation between temperature and restless movement within the same sleep stage.

The duration of the study, currently at two days, is insufficient to draw robust conclusions. Extending the duration will provide more reliable data. Moreover, increasing the diversity of participants, particularly across different age groups, will enhance the generalizability of our findings. Conducting experiments in a lab setting would ensure greater adherence to experimental controls and reduce the impact of external variables.

Further research is needed to solidify these conclusions and explore the practical applications of this technology in enhancing sleep quality.

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