| Title | RhythmSleep : a smart thermal blanket for sleep quality improvement |
| --- | --- |
| Sub Title | |
| Author | Lu, Zihan(Minamizawa, Kouta)<br>南澤, 孝太 |
| Publisher | 慶應義塾大学大学院メディアデザイン研究科 |
| Publication year | 2022 |
| Jtitle | |
| JaLC DOI | |
| Abstract | |
| Notes | 修士学位論文. 2022年度メディアデザイン学 第967号 |
| Genre | Thesis or Dissertation |
| URL | https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KO40001001-00002022-0967 |

Master's Thesis
Academic Year 2022

# RhythmSleep: A Smart Thermal Blanket for Sleep Quality Improvement

Keio University
Graduate School of Media Design

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A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

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Abstract of Master's Thesis of Academic Year 2022

# RhythmSleep: A Smart Thermal Blanket for Sleep Quality Improvement

Category: Design


## Summary

Sleep is a natural state that takes up one third of human lifespan. And the quality of it is directly associated with the performance on the next day. In order to improve the sleep quality, factors that could possibly affect sleep quality need to be considered. In this research, temperature is chosen as the solution. During sleep, temperature influences the sleep quality through the microclimate surrounding the bed, which means the temperature of the whole sleep process can be modified to help people have a better sleep.

One part of the microclimate, the blanket, was decided as the form of the prototype. The final prototype could give different thermal outputs by different body parts in different sleep periods. It was designed in a specific shape so that it can suit many sleep positions without the assistance of other sensors. In the nap experiment, the result of the test group showed that this prototype could improve the sleep quality both subjectively and objectively.



Keywords:

sleep quality, blanket, ambient temperature, microclimate, nap



Keio University Graduate School of Media Design

Zihan Lu

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# Acknowledgements

First I would like to express my sincere gratitude to my supervisor Professor Minamizawa Kouta and sub supervisor Professor Yun Suen Pai for their kind and continuous support of my master study and research. Professor Minamizawa Kouta gave me a lot of inspiring and informative guidance whenever tough problems or obstacles occurred. His perspicacious insight and profound knowledge helped my a lot in research directions, research focuses and research structure. Professor Yun Suen Pai spared a lot of time for my research throughout the design and proof of the research concept. He devoted a lot of help in solving problems that appeared in prototype and experiment design. He also gave a lot of equipment and devices related support to my research.

Besides my advisors, I would like to thank Professor Akira Kato for reviewing my master thesis, warmly understanding my situations and offering much thoughtful and helpful advice in improving my research and thesis content. I would also like to thank Professor Sohei Wakisaka and Professor Midori Kawaguchi for their help for my thesis defense.

Then I would like to thank those in the hacking studio that offered me a lot of support in the process of my prototype making and experiment conducting (in the order of time). Thank George Chernyshov for explaining every detail about the PCB I need to disassemble and solving the tech problems of my prototype. Thanks a lot to Chen Kanyu for spending time discussing my research details, supporting my nap experiment, participating in every experiment and offering the sleep pads. Thank Wang Ziyue for solving the tech problems and offering help in thesis structure. Thank He Yan for supporting my research and helping me in research video making.

Lastly I would like to thank all the participants of my experiment (in the order of time), Peng Danyang, Wong KehFei, Chen Kanyu, Wang Keyu, Chen Siying, Wang Ziyue and Ma Hua. Thank you for your kind help!

# Chapter 1
# Introduction

## 1.1. Background and motivation

Sleep is a topic that is related to everyone in the world. Although a consensus has not been reached yet about the exact purpose of sleep, there is no doubt that sleep is an important biological process that is beneficial for health, restoration and cognition development [1]. However, the quality of sleep affects the functions of sleep and varies from person to person. Many factors, external or internal, might lead to poor sleep quality and therefore, affect the quality of life during the wakefulness. Some of the factors related to the sleep disorders, especially the psychological problems like stress, depression and anxiety, would lead people into a vicious circle.

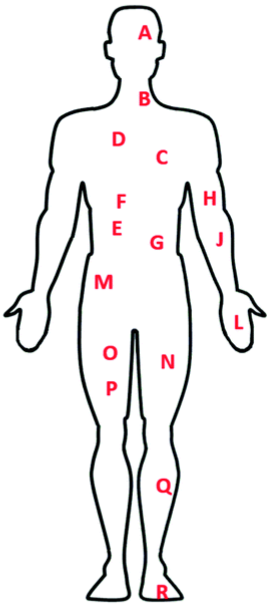
Among all the environmental factors related to sleep quality, light, noise, bed comfort and etc., temperature seems to be the factors that is easy to manipulate with and at the same time, related closely with sleep stages and many biological processes. As the temperature sensors in the human body are distributed in every piece of skin, temperature variation would also have a much larger influence in both breadth and depth compared with other environmental factors. During sleep, temperature and humidity are also responsible for the formation of microclimate around the bed, which is directly associated with the sleep experience and quality. Through the microclimate, the ambient temperature is possible to influence core body temperature through its impact on the skin temperature and the thermoregulation process controlled by hypothalamus [2].

The core body temperature is regulated under a 24-hour cycle called circadian rhythm. The variation of the core body temperature is almost in accord with the temperature variation in nature. Not only the scientific experiments showed the strong connection of the circadian rhythm with sleep, an anthropology research paper based on the observations of three preindustrial societies also revealed similar findings. Gandhi Yetish et al. [3] studied people living the traditional lifestyles that resemble those of our ancestors before the Industrial Revolution in San(Namibia), Tsimane(Bolivia) and Hadza(Tanzania). They found that these peoples did not sleep more than "modern" humans, with average durations of 5.7–7.1 hours. But their insomnia rate was much lower than people in industrial societies. When anthropologists tried to analyze the sleep patterns of these people, it showed that they went to sleep several hours after sunset and awakened around sunrise and neither sleep onset nor offset were tightly linked to solar light level. After adding the factor temperature into the study, the regularity became clear. These preindustrial people always initiated their nocturnal sleep during a period of falling ambient temperature and started to wake near the nadir of the daily temperature rhythm, which means during sleep, their body did not need to actively shed heat to reduce the core body temperature. This research indicated that by building a temperature regulation similar to the natural state, it is possible to improve the sleep quality of modern people.

## 1.2. Problem statement

The future of sleep related research is always to elucidate the biological mechanism behind any factors related to sleep process to uncover more secrets of how the human body evolves and functions in the process of adapting to modern life. And the focus on temperature would promote the sleep associated industries to find more solutions to offer a better sleep for people who need it. Nowadays, with the development of technology and a deeper understanding of sleep itself, the research on the impact of temperature on sleep has already reached the neural and metabolic level. Still, a lot of work can be done to further explain the temperature impact on sleep in a systematic way and to find better solutions to finally improve the sleep quality.

Currently, the research methodologies for the impact of temperature on sleep can be divided into three categories. The first is to analyze the influence of constant ambient temperature on sleep quality, which often refers to the occupied proportion of changes sleep stages and the times of wakefulness. The second methodology is to apply different ambient temperatures for different sleep stages to see the differences of sleep quality and sleep duration with the constant temperature group. The second methodology is based on the research results of the first methods and involves more variables. The third methodology in this field focuses on the local parts of the human body. By passive heating specific parts of the body before or during sleep, the research could reveal the effects of this action on the core body temperature, distal skin temperature, sleep onset or sleep quality. The third methodology emphasizes the circadian rhythm more than the previous two methodologies.




| Skin Location | Cold (15°C) | Room (27°C) | Hot (47°C) |
|---|---|---|---|
| Forehead (A) | 31.7 | 35.2 | 37 |
| Back of Neck (B) | 31.2 | 35.1 | 36.1 |
| Chest (C) | 30.1 | 34.4 | 35.8 |
| Upper Back (D) | 30.7 | 34.4 | 36.3 |
| Lower Back (E) | 29.2 | 33.7 | 36.6 |
| Upper Abdomen (F) | 29.0 | 33.8 | 35.7 |
| Lower Abdomen (G) | 29.2 | 34.8 | 36.2 |
| Tricep (H) | 28.0 | 33.2 | 36.6 |
| Forearm (J) | 26.9 | 34.0 | 37.0 |
| Hand (L) | 23.7 | 33.8 | 36.7 |
| Hip (M) | 26.5 | 32.2 | 36.8 |
| Side thigh (N) | 27.3 | 33.0 | 36.5 |
| Front Thigh (O) | 29.4 | 33.7 | 36.7 |
| Back Thigh (P) | 25.5 | 32.2 | 36.0 |
| Calf (Q) | 25.1 | 31.6 | 35.9 |
| Foot (R) | 23.2 | 30.4 | 36.2 |

(Reported human skin temperatures for different points on the body at varying ambient temperatures. Source: Suarez, Francisco, et al. [4])

Figure 1.1 Skin temperature distribution under different ambient temperature

These three methodologies share the similarity that they all see temperature as a one dimensional factor that influences sleep, rather than a factor that can be segmented for different body parts and then combined together to have a multi-dimensional impact on the human body. To be more specific, the distribution of skin temperature of humans varies according to both the distance to the main body and the ambient temperature(Figure 1.1). But the core body temperature would, in most cases, remain constant despite the environment temperature, which is the result of thermoregulation, a systematic process that involves many organs for one purpose, the core body temperature, acting as the basis of many temperature related research. However, thermoregulation is not the only temperature-related biological process in the human body and the hypothalamus is also not the only region in the brain that responds to the temperature variation. To explore more possibilities of how temperature influences the sleep process, it is necessary to not to take the temperature as a simple factor that is only related to core body temperature.

## 1.3. Research question and research goal

Given that the topic of this research is to figure out the influence of dynamic and segmented temperature on sleep, the big research question is quite obvious: How do the different thermal outputs by body parts and by sleep states alter the sleep quality? The big research question covers three smaller questions: How to distinguish thermal zones under different sizes of human bodies? How to arrange the thermal outputs in different sleep stages? And how to measure sleep quality of different people and compare between these data?

The ultimate goal of this research is to improve sleep quality under the multiple effects of temperature. To be more specific, the research goal can be described as:

- Find an appropriate media to convey the segmented thermal outputs to different body parts.
- Find a proper method to make sure the thermal outputs fit most sleep positions.
- Find a suitable solution to arrange the thermal outputs under different sleep states.

## 1.4. Thesis structure

This thesis is composed of five chapters, all related to two key words, temperature and sleep quality. Below is the brief description of each chapter.

- Chapter 1 talks about the gaps of current temperature related sleep studies and the direction of this research.
- Chapter 2 gives more scientific knowledge about functions of sleep, effects of temperature on sleep and a bit about naps. In the part of 'Thermal effects on sleep', mechanisms of the arrangement of temperature on different body parts and on different sleep stages is explained.
- Chapter 3 concretizes the form and functions of the prototype. It contains the initial small scale prototype with flex sensors and some heat detection and emission elements for the attempts of realizing the partial functions and of getting similar with Arduino and Matlab. After analyzing the result and feedback of the initial prototype, the process of making the final full-size prototype is also introduced in this chapter.
- Chapter 4 is mainly about the assessment of the final prototype and the conduction and evaluation of sleep experiments using this prototype. The experiment eventually used the one-hour nap as the experiment content. The evaluation of sleep quality is separated into subjective parts and objective parts.
- Chapter 5 reiterates the research goal and summarizes and concludes the whole sleep process.

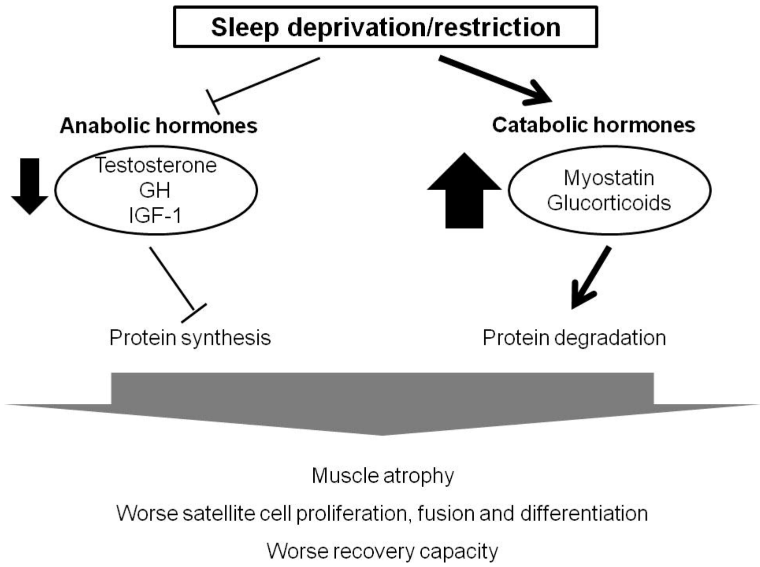
# Chapter 2
# Literature Review

## 2.1. Sleep functions

Sleep is a natural repairing and regulating process that is undergone by almost all the creatures at most of the time reducing the activity both physiologically and mentally to help recovering from the unbalanced hormone or neurotransmitter level. To be more specific, in the bodily aspect, some research has shown that sleep is beneficial for muscle damage recovery [5], tissue growth and healing [6], regulation of respiration and circulation [7] and etc. On the other hand, sleep also shows great impact on cognitive performance [8], memory and learning process and emotional regulation [9].

### 2.1.1 Muscle repair and tissue restoration

The procedure of muscle repair and tissue growth or repair during sleep are the consequence of hormonal changes in the cellular level. Several sleep deprivation experiments on rats indicated that the molecular markers of muscle repair such as insulin-like growth factor 1 (IGF-1) would decrease rapidly during the 8h of sleep deprivation thereby inhibiting the growth of muscle and promoting protein reductions [5, 10, 11]. Carol A Landis and JoAnne D Whitney [12] conducting another experiment on wound healing showed that after several days of sleep deprivation, inflammation areas developed on the paws and tails of the rats and the inflammation turned into ulcers if the sleep deprivation extended to several weeks. The similar process happens on humans as well. After the intense training or match, athletes who encountered sleep deprivation would have a higher level of inflammatory responses compared with athletes without sleep deprivation. Such sleep deprivation would also cause the increase of body pain [13]. The possible mechanism behind these observations involves IGF-1/PI3K/Akt and mTOR (mammalian target of rapamycin) pathways mediated by IGF-1, the characteristic element in muscle protein synthesis, and testosterone, the inhibitor of myostatin. The upgrading level of cortisol/corticosterone resulting from the sleep deprivation would also increase the muscle atrophy and reduction of the muscle protein synthesis, which would break the balance of the relative rates of protein synthesis and degradation, especially during the muscle recovery process (Figure 2.1) [5].



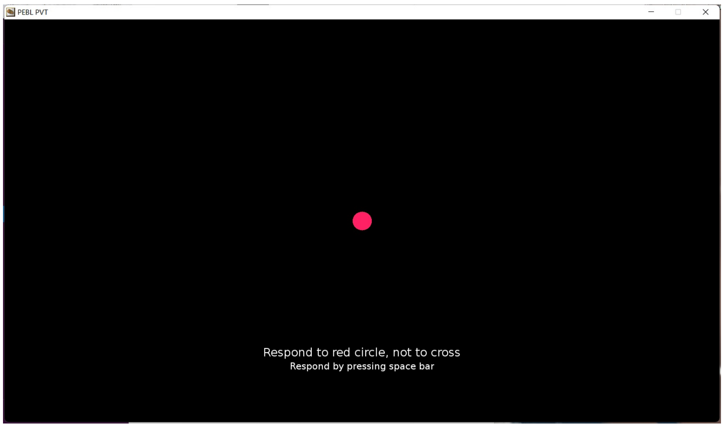

(Schematic representation of the effects of sleep debt on skeletal muscle metabolism. Source: Dattilo, Murilo, et al. [5])

Figure 2.1 Sleep deprivation and muscle repair

### 2.1.2 Cognitive performance

Cognition refers to a mental process that acquires and understands knowledge through the ways of sensing, thinking and experiencing. It normally contains many aspects like sensory perception, attention, judgment, planning, reasoning, problem solving and decision making. Sleep is proved to be closely related to kinds of cognitive performance. Sleep deprivation for one to several nights would show a great impact on the basic cognitive capacities like alertness, vigilance and attention [14].

Psychomotor Vigilance Test (PVT) is the most widely used method to evaluate behavioral alertness in the sleep deprivation study because of its high sensitivity and reliability over other measurements. It measures alertness and vigilance by recording the reaction time to visual stimuli with random intervals (the intervals are usually several seconds) in several minutes (Figure 2.2) [15]. The test is normally conducted to require the participants to press the button as soon as the light shows up. The mostly used PVT lasts 10 minutes, but Devon A Grant et al [16] found that 3-minute version of PVT in smartphones or tablets also acts as a reliable measurement in the sleep deprivation study.




(Source: PEBL software)

Figure 2.2 Interface of PVT test

As to the measurement of attention in cognitive ability, hand-eye coordination, which requires the simultaneous use of hands and eyes, can be a useful tool. Drew Dawson and Kathryn Reid [17] studying the relationship between wakefulness and attention compared the performance in the hand-eye coordination test of two groups of participants, one stay awake for up to 28 hours and the other drank 10 to 15 gram of alcohol every 30 minutes. The result of this study showed that from the 10 to 26 hours of continuous wakefulness, the attention performance of the participants was equivalent to the performance with a 0.004% per hour increase in blood alcohol concentration. And performance of 24 hours awake participants was equivalent to the level of that of a blood alcohol concentration of roughly 0.10%.

Such a level is considered as obvious physical impairment and loss of judgment and is illegal in most countries to drive.

### 2.1.3 Memory and learning

Memory and learning are closed related functions in processing information. Memory aims to encode, store and retrieve information while learning aims to acquire and understand information. They also have some overlap with cognitive performance. Based on the development of neuroimaging, the study of brain activity can be continuous and accurate to different brain areas during different sleep stages, making it possible to reveal more detail in covert processing of memories after learning [18].

Some research showed sleep had a positive impact on the motor procedural and declarative memory in the process of learning and memory. Declarative memory refers to the conscious procedure to learn and store information in the brain for several minutes to a lifetime. The three subprocesses of long-term memory, encoding, consolidation and retrieval, each of which are related to different sleep stages and can be impaired by sleep deprivation [19]. A research showed that after 36 hours of deprivation, the retention ability was significantly impaired and cannot return to the normal level with the caffeine intake. Such a result is generally explained as the function of REM sleep for memory. It is also found that besides the benefits of sleep on consolidation after learning, sleep also plays an important role in preparing specific brain networks for initial encoding for a range of verbal and visual materials. James N Cousins and Fernández Guillén [18] concluded that total sleep deprivation would show a deficit in the capacity to encode pictures, verbal word lists and face pairs.

### 2.1.4 Emotion

Sleep and emotion have an intimate relationship as sleep is both a common symptom and risk factor for almost all psychotic and neurological disorders. Sleep loss is found to amplify negative emotions, reduce the occurrence of positive emotions by decreasing the possibility to situate oneself in a positive emotional environment. Sleep loss would also alter the ways of understanding, expressing and switching emotions, and would exacerbate the mood disturbances like anxiety, anger and depression [20, 21].

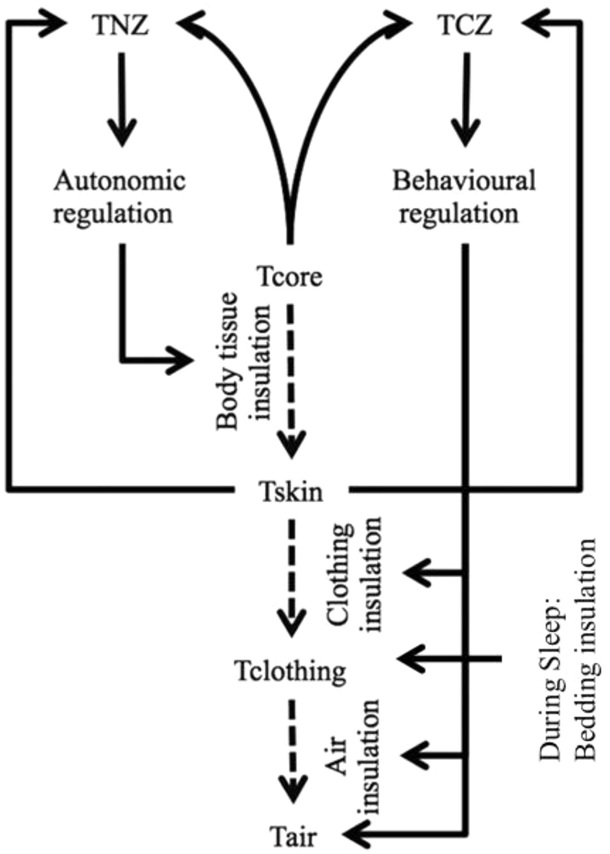
To monitor and evaluate emotions, physiological measurements like electrocardiogram (ECG) and Galvanic Skin Response (GSR) can be used as reliable methods. ECG can provide information for the evaluation of the electrical activity of the heart and is influenced by both the sympathetic and parasympathetic functions. However, GSR can reveal the data for the sweat glands function and is influenced by the sympathetic function. ECG is considered as a more accurate measurement than GSR in the emotion classification. And the combination of these two measurements would offer better results and provide simple, effective and continuous recording to identify the physiological states of the testers [22].

## 2.2. Thermal effects on sleep

The thermal effects related to sleep are mainly three aspects, the ambient temperature(TA), the skin temperature(TSK) and the core body temperature(CBT). During sleep, these three aspects(factors) are interlocked and influence each other with other factors like the humidity, airflow, clothing and adiabaticity of the bedding. Normally, at the beginning of the sleep, the core body temperature would gradually decrease and reach the nadir at about 6 h after sleep onset. At the same time, the temperature of skin temperature, especially the temperature of distal skin, would increase to maintain the heat loss and heat production balance with the core body temperature [23].

### 2.2.1 The relationship of TA, TSK, CBT and their influence on sleep

Skin temperature acts as the intermediate variable between the ambient temperature and core body temperature. It is the manifestation of the heat production, mainly controlled by the core body temperature regulation brain portion hypothalamus, and heat loss of the body, the heat exchange with the environment. Normally, the ambient temperature would not affect the core body temperature of warm-blooded animals, but if the ambient temperature causes large variation in skin temperature in a short time, the core body temperature will also be influenced, which in severe cases, would lead to heart stroke or hypothermia.

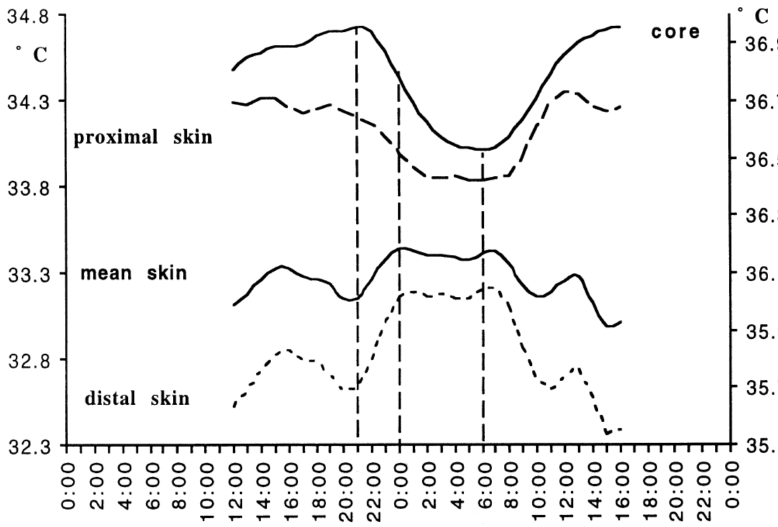



(Schematic overview of autonomic and behavioral control of thermal insulation. Solid arrows denote relation and/or control and dashed arrows denote heat flow (Kingma, Boris RM, et al. 2014). TNZ=thermal neutral zone, TCZ=thermal comfort zone, Tcore=core body temperature, Tskin=skin temperature, Tclothing=clothing insulation, Tair=ambient temperature and airflow. Source: Caddick, Zachary A., et al. [24])

Figure 2.3 Formation of microclimate in bed

A better sleep experience can also be obtained by creating an optimal surrounding microclimate to achieve the ambient thermoneutrality through the use of bedding and clothing. Thermoneutrality means the equilibrium point of heat production and loss, occurs at an ambient temperature from 27.9 to 28.5°C in humans during sleep. Such temperature range allows the body to maintain the optimal state of core body temperature and skin temperature. Ambient temperature above this range would cause sweating and the temperature below this range would cause shivering, both of which would cause people to wake up from sleep. Compared with a cold environment, high temperatures in an ambient environment are more likely to cause the change in the sleep structure and more night waking. Experiments related to the usage of electrical blankets proved this finding [24]. The ambient thermoneutrality in microclimate is related to the adiabaticity of clothing and bedding, which can be modified through the thickness, materials or by directly changing their temperature (Figure 2.3) [25].

### 2.2.2 Circadian rhythm




(The upper panel shows smoothed average human temperature curves as measured under constant routine conditions (Krauchi and Wirz-Justice 1994) for both core (upper curve), proximal skin (second curve), mean skin (third curve), and distal skin (lowest curve). Source: VanSomeren, Eus JW. [26])

Figure 2.4 Circadian rhythm

Circadian rhythm is a natural, internal process that regulates the sleep-wake cycle and repeats roughly every 24 hours. In body temperature, circadian rhythm expresses as regular variation of core body temperature through heat production and heat loss. During the day when people are awake, the core body temperature slowly increases until the peaks around 4 pm to 8 pm. At night, the core body temperature starts to decrease through heat loss from core body to distal body, leading to the increased skin temperature in hands and feet. As a result, the variation of core body temperature corresponds with temperature change of proximal skin, but opposite to that of distal skin (Figure 2.4) [26].

The variation of circadian rhythm on core body temperature is the result of the self-regulation process called thermoregulation. It is a process that is mainly controlled by hypothalamus through the communication between the neural centers, peripheral sensors and effector organs. When the skin sympathetic neurons sense cold or hot, it would send the signal to hypothalamus. Depending on the type of the signal, hypothalamus would either increase sweating to lower the body temperature or raise skin blood flow and make skeletal muscle shiver to warm the body [27].

The possible mechanism behind the influence of circadian rhythms on sleep is that the temperature variation turns into the thermal input on those thermal sensitive neurons and provides a signaling pathway for the circadian modulation of sleep and wakefulness. On the other hand, warming of the skin is associated with an activation of sleep in the brain structure like midbrain reticular formation, hypothalamus, and cerebral cortex. Thus, by modulating the thermo-sensitive neurons in the skin, it is possible to promote sleep or wakefulness in the human body [26].

### 2.2.3 Passive body heating

Based on the evidence of the relationship between body temperature and sleep, the sleep onset was found to be closely related to the sudden temperature change in proximal and distal skin. As a result, both the elevation in skin temperature and fall in core body temperature are crucial to sleep. Passive body heating can manipulate skin temperature to cause the vessel dilation and body temperature fluctuation and thus influence the sleep onset, sleep duration and sleep structure [28].

The passive heating methods that reported related to the sleep onset contain hot showers [29], foot bathing [30] and local warming in the forehead ( [31] and periocular skin [32]. Normally, the whole body passive heating would increase both core body temperature and skin blood flow but local passive heating would not affect the core body temperature. But some research also found that if the temperature of the foot bath is above 41°C , it would still have some impact on the core body temperature making it harder to decrease during sleep. As a result, to promote better sleep, it is important to control the temperature of the foot bath for a better heat dissipation and sleepiness inducement [33]. The passive heating in the forehead during sleep is called frontal cerebral thermal therapy. It is reported to have the similar effects on sleep induction compared with the hypnotic treatments with barely side effects [31]. Periocular skin warming is also able to improve the sleep quality both objectively and subjectively by shortening the sleep onset latency. Periocular warming can increase distal skin temperature while not affecting the proximal skin or core body temperature, thus increasing the distal-proximal skin temperature gradient, which benefits sleep [34].

### 2.2.4 Ambient temperature

Nowadays, the research about the effects of ambient temperature on sleep has turned from the limited study of the constant environment temperature on whole nocturnal sleep to variable temperature based on different sleep stages [35–37]. The criteria of different sleep stages is determined by the real-time physiological signals like electroencephalogram(EEG), electrooculography(EOG) and heart rate variability(HRV). The sleep can either be divided into non-rapid eye movement(NREM) sleep and rapid eye movement(REM) sleep or more precisely four sleep stages. And the temperature regulation system could be the air conditioner or designed bedding.

There are also many products on the market that use ambient temperature to improve sleep quality like smart mattresses that provide cooling or heating functions like Pod Pro Mattress[1] and Chilisleep[2]. But all these research prototypes or products provide the whole body the same thermal stimuli and do not have interactions with the variation of the users' body temperature, which have some

1 Pod Pro Mattress `https://www.eightsleep.com/product/pod/`

2 Chilisleep `https://www.chilisleep.com/products/ooler-sleep-system`

space to be improved.

## 2.3. Effects of Nap

Nap is a short period of sleep that normally occurs in daytime and lasts from a few minutes to a few hours. It is considered to be the daily routine of infants and children as naps are crucial for their brain development. Still many adults keep this habit in their whole lifespan [38].Naps are categorized into mainly three types, the prophylactic nap (prepare for sleep loss), the replacement nap (response to sleep loss) and the appetitive nap (for enjoyment) [39].

### 2.3.1 Benefits of napping

Naps between 10 to 45 minutes can help restore both body and mind. Normally, a short nap would only lead people to the rapid eye movement sleep, the relatively light stage where the brain actively processes different information and consolidates memory [40]. Similar to nocturnal sleep, naps also benefit following learning, cognitive performance and emotional state. Compared with caffeine, the prophylactic nap can provide longer-lasting improvements on performance, emotion and alertness. Naps also showed the edge over caffeine on the advancement of declarative verbal memory [41].

### 2.3.2 Nap and circadian rhythm

Naps are also influenced by circadian rhythm. The recommended time for a daytime nap is between 1pm to 4pm, while the optimal time is around 3pm as the circadian rhythm at that time starts to decrease [42]. Research of Catherine E Milner and Kimberly A Cote [38] on the relationship of naps and wakefulness showed that naps after 6 or 18 hours of wakefulness have more benefits than those after 30, 42, or 54h of wakefulness. The possible reason for this finding is that naps after a few hours of wakefulness would help prevent the decrease of body temperature with extended wakefulness. On the other hand, naps too close to the normal sleep time would impact the circadian rhythm and cause insomnia.

# Chapter 3
# Concept Design

## 3.1. Inspiration and vision

The study of the relationship between temperature and sleep can be traced back to 1845, in the research paper On the Temperature of Man written by British physician John Davy [43]. In that article, Davy talked about the temperature variation during the 24 hours and found that the body temperature would reach the lowest point at midnight. Although he only conducted the temperature measurement on one research object - himself, this article still revealed some important facts about how body temperature changes in different conditions. Then, not until the mid 20th century, systematic research discussion about the effects of thermal on humans started to be conducted and more and more findings and results showed that temperature played an important role during the whole process of sleep.

These days, the research about the effects of thermal on sleep has focused on a more precise temperature manipulation based on different sleep stages or sleep patterns. And the variation on temperature of different body parts has also been discussed and studied under different conditions among different people. There is also much research exploring no-medicine involved methods with barely no side effects to influence the circadian rhythm before and during sleep to shorten the sleep onset legacy or improve the sleep quality. Besides, many sleep-related statistical studies have developed criteria for the high-quality and well functional sleep.

In the future, with a deeper understanding in the biological field of how the human body controls and modifies itself in the sleep-wake cycle, it would be possible to develop new applications or more accurate therapies targeting different needs or sleep problems. Now the gap between this future and nowadays research is about how to organize all these factors related to sleep and find a balance between different sleep criteria. For this research, I only focus on the thermal effects of the ambient environment to influence both the skin temperature and core body temperature to help people get an ideal sleep with shorter time to fall asleep, easier wake and better restoration.

## 3.2. Concept design analysis

Since this research focused on the thermal effects on sleep under the principle of circadian rhythm, there are several questions that need to be considered under this concept. These questions are:

- In which form the thermal energy is conveyed into the human body?
- How to organize the thermal energy?
- How to control the distribution of the thermal energy so that it would work efficiently?

To answer the first question, it is necessary to think about what is required under a normal sleep condition. In most cases, people would need a bed, a mattress, a blanket and a pillow. For people who have a higher need in hygiene, they would also prepare the bedclothes sets and pajamas. Among all the stuff mentioned above, beds and pillows are the first two things to be excluded for the poor mobility and limited contact area with people. Pajamas seem to be an ideal choice for this concept as they can cover most areas of skin to potentially make the thermal energy most effective compared with all other bedding. However, limited to the technique, it is hard to embed wires, modules and sensors into the pajamas and still ensure they are thin, comfortable, safe to use and at the same time able to withstand normal detergents and washing programs. The restrictions of bedclothes are almost the same as the pajamas. As a result, mattresses and blankets are the left two options which are feasible, operable and also functional for the concept. Compared with the mattress, the blanket has a larger contact area with the human body and is relatively easier to carry, so finally the form to convey thermal energy is the blanket.

The second question involves the basic principles of this research, the variation of circadian rhythm and skin temperature distributions of human beings. As mentioned in the literature review, during the period of starting the sleep to falling asleep, the temperature of core body temperature would decrease and the temperature of distal skin temperature would increase, which indicates the sleep onset. Before people wake up, the temperature of the core body would increase and the distal skin temperature would decrease to prepare for wakefulness. These two facts mean that the temperature distribution and variation tendency are opposite in the beginning and end of sleep. So, in the design of this research, when it works as the sleep aid, the temperature in the part for the main body would be lowest and in the part for extremities would be highest (Figure 3.1); while when it works as the wake aid, the distribution would be reversed (Figure 3.2).

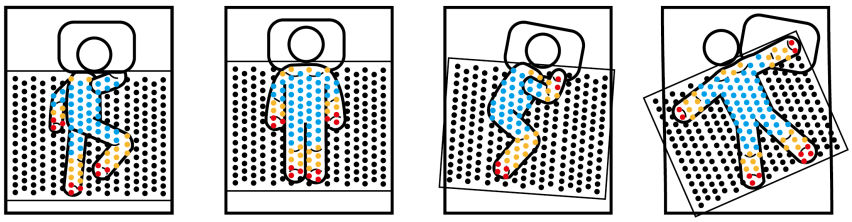


Figure 3.1 Diagram of sleep aid

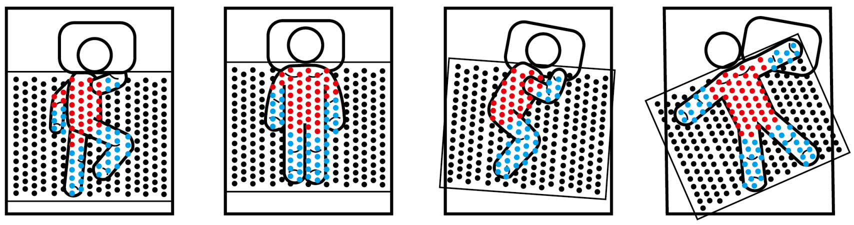


Figure 3.2 Diagram of wake aid

Before answering the third question, the term ‘thermal avatar’ needs to be explained first. The word ‘avatar’ in computing refers to the graphical representation of the user, which is based on the visual concept. For example, in a game, the virtual character that a player can control or manipulate is the avatar of that player. And the thermal avatar also represents the user, not visually but thermally. To be more specific, it means the thermal representation of the target people based on thermal mapping of skin temperature across the body. Under the sleep circumstance, it is required to capture the sleep positions of the users to make sure the thermal energy is given to the exact body parts with the exact amount. So a precise thermal mapping system is required to implement the concept.

## 3.3. Initial prototype: Small scale blanket with partial functions

### 3.3.1 Concept design

The goal for this research is to build a full-size blanket that is able to manipulate the skin temperature of different body parts based on the whole body skin mapping and position capture. However, in the very beginning of the prototype designing, it is necessary to choose the fitting sensors, electrical elements or modules in order to ensure that most functions of the prototype can be accomplished. It is also important to test, evaluate the initial prototype and make improvements based on the result.

Still, the concept design for the initial prototype should take the three questions mentioned above in the Concept Design Analysis into consideration and find the applicable solutions that are possible to begin with. Since in the analysis, it has been certain that the form of the design would be a blanket, the form for the initial prototype would also be something that resembles a blanket. The second question is about how to organize the thermal distribution. However, in the initial prototype, the focus of the solution can be simply to take the thermal output under control. And the third question is about how to realize the detection part and control the whole system under the detection. Sensors and microcontrollers are required to accomplish this goal.

### 3.3.2 Prototype design

The design missions for the initial prototype is

- Able to distinguish simple sleep positions like sleep on back and sleep on side
- Able to sense skin temperature in different parts
- Able to provide different intensity of thermal energy

To correspond with the three missions, I chose three flex sensors for the position distinction, three Lmt70 temperature sensors and three heating wires for the thermal energy release. Below is the sketch diagram of the initial prototype (Figure 3.3).

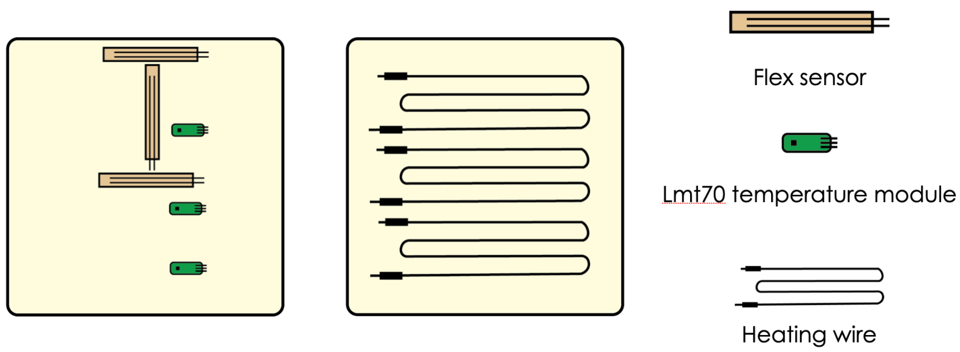



Figure 3.3 Diagram of the initial prototype

Two of the flex sensors were placed parallel and the left one is placed between them and also perpendicular to them. They were designed to detect the degree of bending in the shoulders, legs and the vertical direction of the upper body, respectively. Normally, the bending degree of shoulders in the position of sleep on back would be smaller than that of sleep on side. Besides, when people sleep on the side, the highest point would be at the crotch. As a result, at the sleep on side position, both the bending degree of the flex sensors in the shoulders and the vertical direction of the upper body would be larger than that at the sleep on back position. The third flex sensor acts as the other supportive parameter for the sleep position determination.

Three Lmt70 temperature sensors were placed in positions that represented abdomen, thighs and calves. Lmt70 is the smallest(0.924mm*0.924mm) and accessible temperature sensors with relatively high accuracy($\pm$0.2 centigrade). However, as both the output pin and size of Lmt70 are too small to handle it or attach it to the prototype, I instead used three Lmt70 modules(50mm*8mm). For the thermal energy output, three pieces of one-meter long silicone heating wires were attached to the three areas where the Lmt70 modules were placed to heat the abdomen, thighs and calves based on the detection of temperature sensors.

The size of the initial prototype is about 40cm*40cm. Below is the figure of the front and back of the prototype (Figure 3.4).

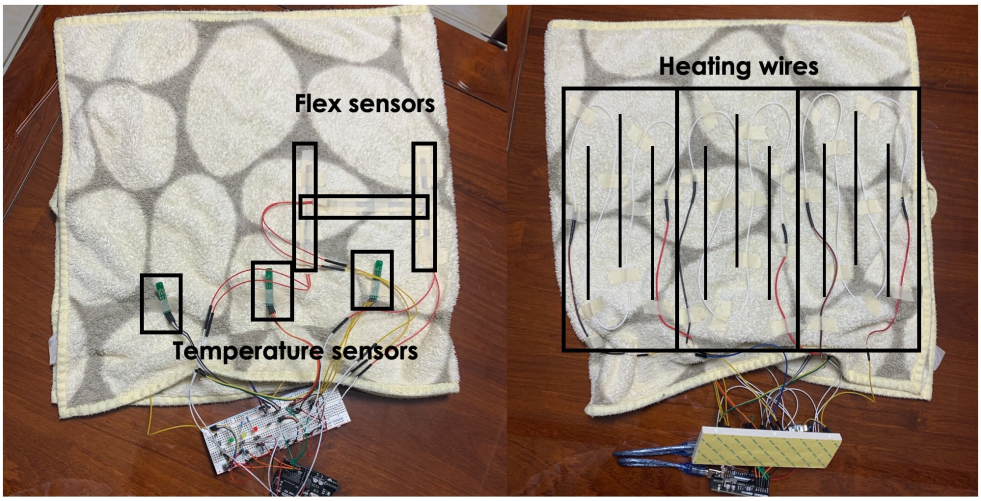



Figure 3.4 Initial prototype

### 3.3.3 Prototype evaluation

To plot the bending degrees of three flex sensors, Arduino Uno is used as the output receiver and Matlab is the data processing software. The three data of the flex sensors worked as three different parameters in three function fragments for the position plotting. The plot did not correspond very well to the real states of the flex sensors, but it could reflect differences of different positions. A toy that fit the size of the initial prototype was placed in the position of both sleep on side and sleep on back and below is the plot for these two positions (Figure 3.5).

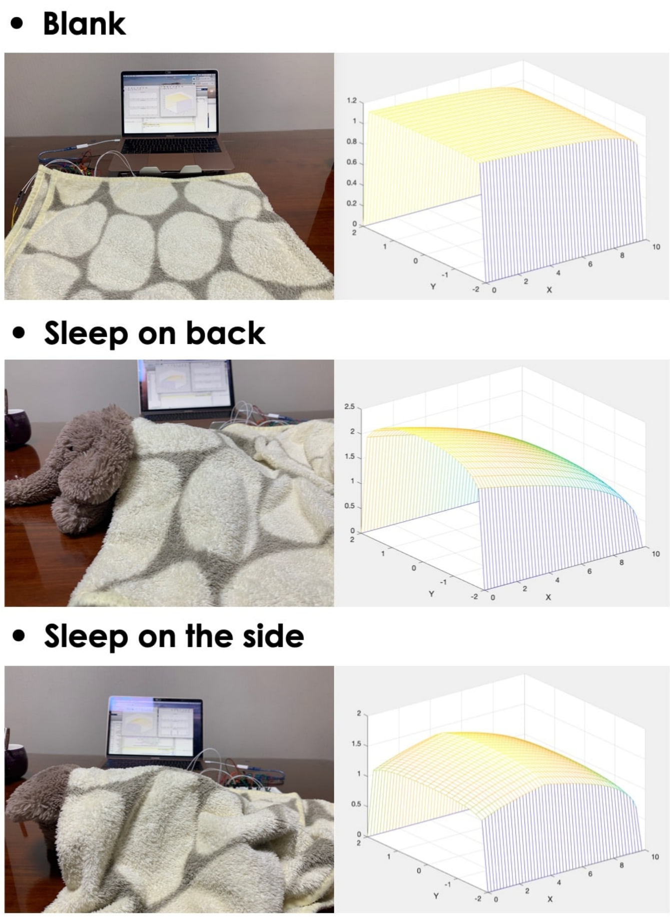



Figure 3.5 Simulation of different sleeping positions using the toy

For the thermal part, I invited my family members to test the initial prototype. The prototype was placed in their arms and thighs. The result showed that they can feel the temperature differences of three sections with thin clothes when the differences are over three centigrade, both in arms and thighs. They also said that the distances between the heating wires were not too large that they felt the heat as the form of area not as the form of lines (Figure 3.6). The plot reflecting the temperature to help understand the temperature variation is here(Figure 3.7).

Figure 3.6 Image for thermal test

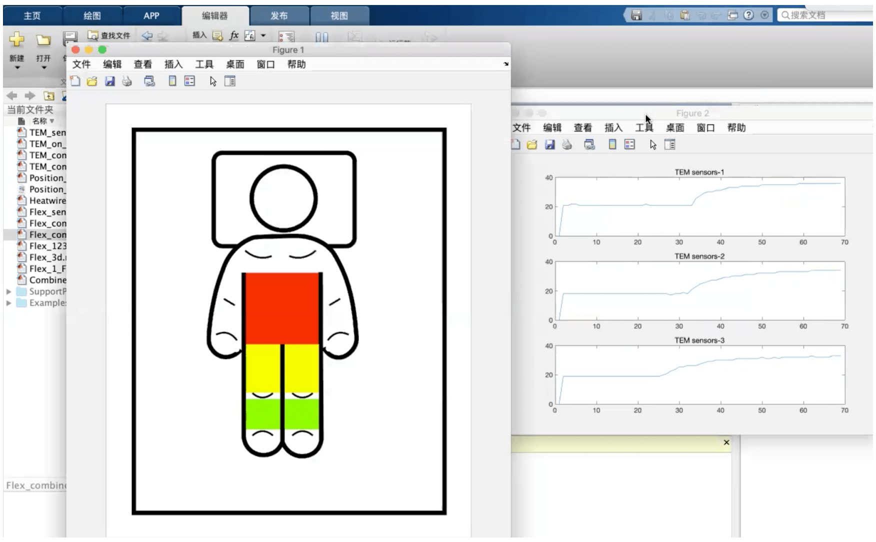



Figure 3.7 Matlab plot of temperature sensors

### 3.3.4 Discussion

Although this initial prototype carried out all the three missions, there are still many problems to be solved before moving to the next full-size prototype. The first problem is related to the size of the initial prototype. The flex sensors worked quite well in the initial prototype as the length of the flex sensor is almost the same as the width of the toy. So the flex sensor can reflect the position of the toy quite well. If I need to apply this design to the full-size prototype, a flex sensor needed would be 40 centimeters long, which is difficult to obtain. Another problem related to flex sensors is that they need to be placed in the exact location to make sure the result of sleep positions corresponds to the users. But normally during sleep, people would not keep one posture until wake up, which makes the following detection of sleep positions to be inaccurate.

The problems of the Lmt70 module are mainly about its size and placement. The base of the Lmt70 module is a hard inflexible printed circuit board with an area of 400mm2, which is more than 400 times larger than the Lmt70 sensor placed on one side of the module. Besides, the length of the module is 50mm, which cannot be ignored compared with the size of human body parts. It is also possible that the Lmt70 sensor doesn't touch the skin during the measurement as the module is placed in the blanket. Another problem comes with the placement of the Lmt70 module is that, what this module measured was not the skin temperature but the surface temperature of the clothes testers were wearing. It can be assumed that the surface temperature would be the same as the skin temperature after a period of sleep if the pajamas are thin. But still, the space between the Lmt70 sensors and skin would cause inaccuracy during the measurement.

Last but not least, in the initial version of the prototype, the part of thermal output is done by the normal heating wires placed parallel and covering the same size of areas. But according to the concept of this research, cooling is necessary to complete the whole design. And the aim of detecting the sleep position is to determine the location of the main body and limbs, so that the blanket would cool or heat certain parts as expected. The remaining problems of how to implement the cooling function and how to correspond the human body parts with the thermal avatar still need to be thought over carefully.

# 3.4. Final prototype

## 3.4.1 Concept design

The final prototype would be a full-size blanket that allows testers to sleep with and at the same time improve their sleeping experience through the hierarchical thermal output. The design focus of the final prototype would be:

- How to detect sleep positions
- How to accomplish the cooling function
- How to place the thermal sensors to ensure the accuracy
- How to organize the thermal output to improve the sleep experience

## 3.4.2 Prototype design overview

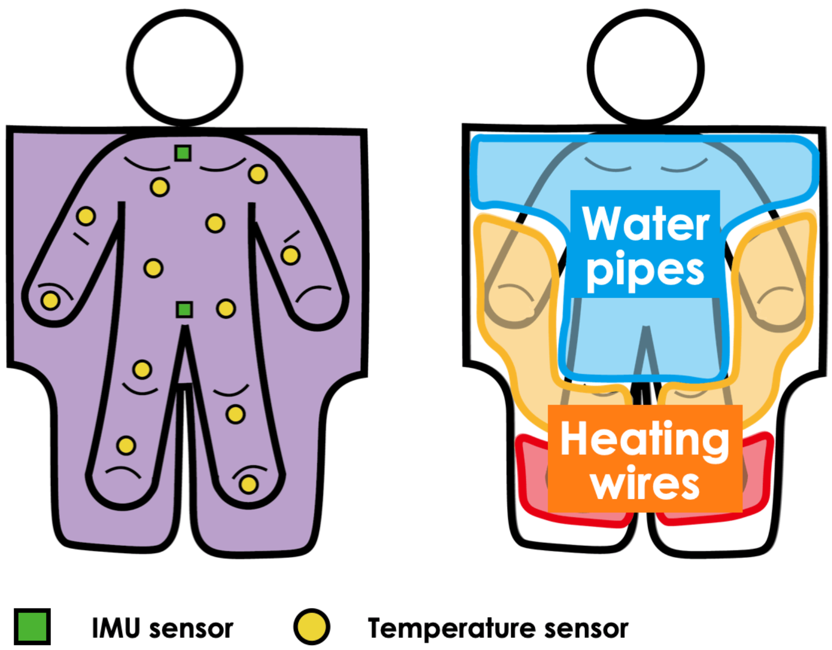



Figure 3.8 Concept diagram for the final prototype

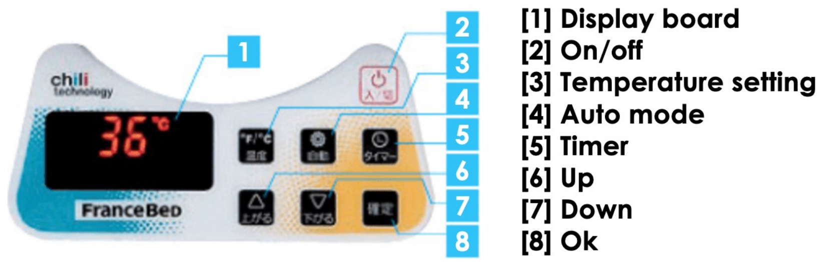
The prototype contains three parts, the electronic device that controls the components, the blanket main body and the system that organizes sensors and components. To be more specific, the electronic device used both the water heating/cooling system and normal heating wires as the thermal output. In the main body of the blanket, the water pipes and wires were placed inside to correspond to the different body parts. Rather than detecting the sleep positions with sensors, I made some changes in the appearance of the blanket to make it suitable for some basic sleep positions. And the whole control system was designed to change the thermal output types and strength based on the sleep states and skin temperature of the testers (Figure 3.8).

### 3.4.3 Prototype design - device part

The device part of the final prototype was designed with two existing products, a water cooling and heating blanket and an electric blanket. The mission in this part is to combine these two blankets together and control the combination through the Arduino hardware.

#### Modification of system unit of the water cooling/heating blanket

The easiest way to control the electronic products is to modify their switches, the part that users can directly interact with. The user interface of the water cooling/heating blanket is a LED display with several press buttons (Figure 3.9).




(Product details source: `https://item.rakuten.co.jp/kaientai/35762100/`)

Figure 3.9 User interface of the water cooling/heating blanket

The structure of the press buttons are capacitive switches, which means when users press the button, the microprocessor inside the system unit would sense the capacitance variation and then give some responses according to the location of the button. As a result, to trigger the capacitive switch, a conductive object is needed to remove part of the charge to change the capacitance. I tried several methods to modify the switch, but the result was not very ideal. So instead of hacking the switches of the blanket, I would need to move my focus to control the electronic components inside the case.

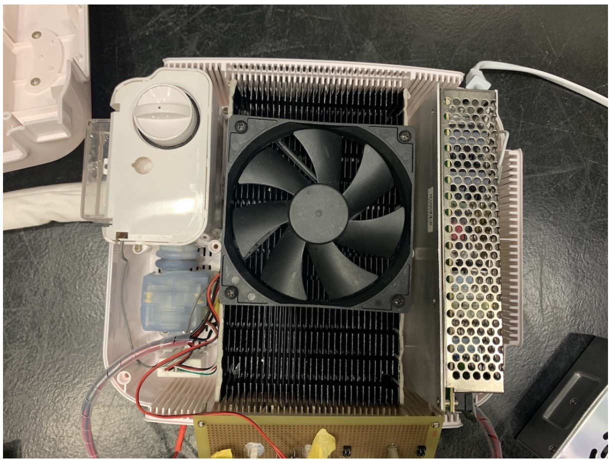


Figure 3.10 Inside components

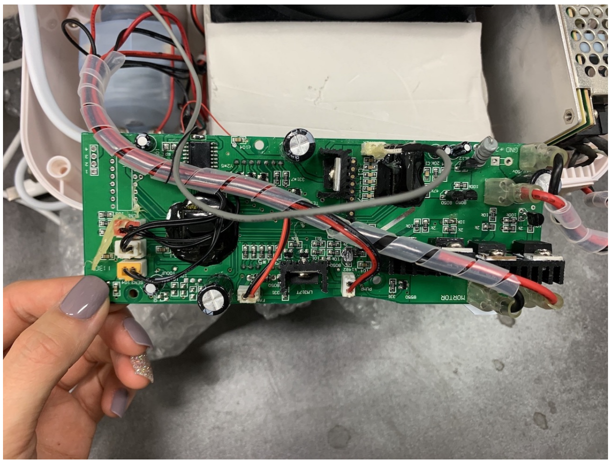


Figure 3.11 PCB that controls inside components

The components inside the case are, from right to left, a switching power supply (AC to DC 24V), a big peltier device (24V), a fan (9V), a pump (9V) and a small water tank (Figure 3.10). They were controlled by a printed circuit board (PCB) placed below the top cover of the case (Figure 3.11).

The components that can be directly moved to another board were the power supply, the fan and the pump. The supplied power is 24V but the fan works under 9V, so a voltage regulator is needed to ensure the constant 9V supply. There was a voltage regulator LM317T in the PCB, so I removed it from the previous board and soldered it to the new board according to the equation and circuit diagram. There are two slide switches in the new board, the one in the middle of the board controls the whole circuit while the one on the right controls the on/off of the peltier device. As the temperature of the peltier device would still be high after it has been turned off, the two switches can separate the peltier device with the fan so that the fan can work to cool down the closed peltier device. Below is the circuit diagram of the new board and the actual board I built (Figure 3.12).

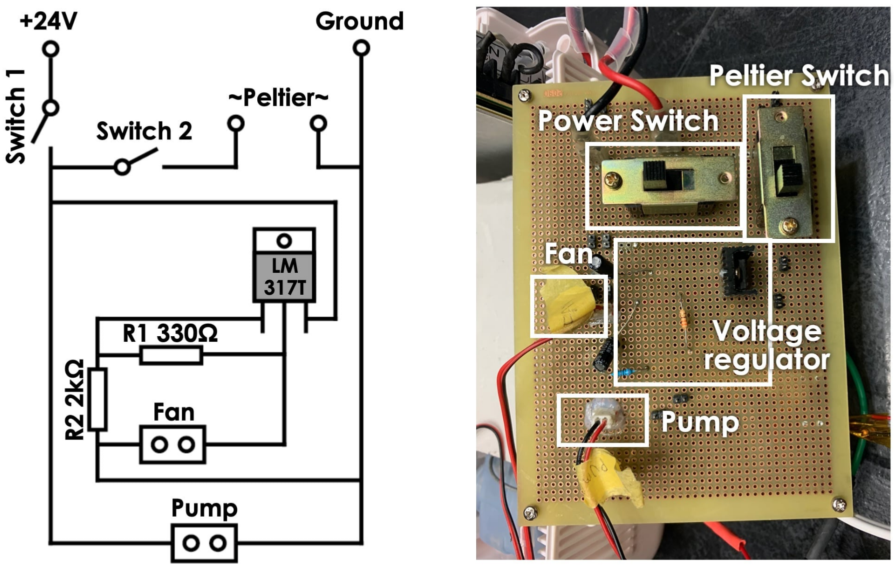



Figure 3.12 Circuit diagram and new board appearance

### Peltier device

There are two junctions in the peltier, between which the heat can be transferred under the current flow. When a voltage is applied to the peltier, heat would be removed from one junction and deposited in the other junction to cause one side to be cool and the other side to be hot[1]. If the heat is not removed from the hot side in time, the cool side would be affected. The direction of the current decides which side to be cool. As a result, by changing the positive and negative interfaces, one side of the peltier can be either cold or hot.

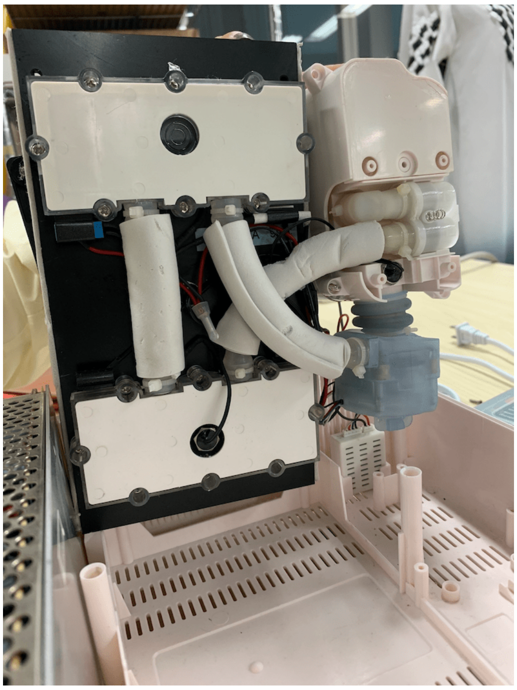
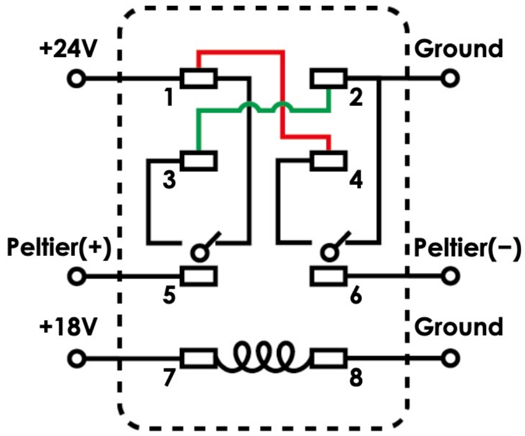


Figure 3.13 Other side of the inside components

In accordance with the water pipes arrangement inside the case (Figure 3.13), it is clear that the bottom side of the peltier device is used to change the temperature of the water. So a switch that is able to change the direction of the current is necessary for my design. There are two options, one is to use DPDT relay and the other one is to use a H-bridge module. Compared with DPDT relay, H-bridge

1 https://ii-vi.com/how_do_thermoelectric_coolers_tec_work/

module is a better choice as it does not have any sound when working and can justify the magnitude of current. However, the H-bridge module I got[2] is somewhat overloaded when applied to the peltier device of the water cooling/heating blanket. So I eventually chose the DPDT relay to control the direction of the current flowing in the peltier (Figure 3.14).



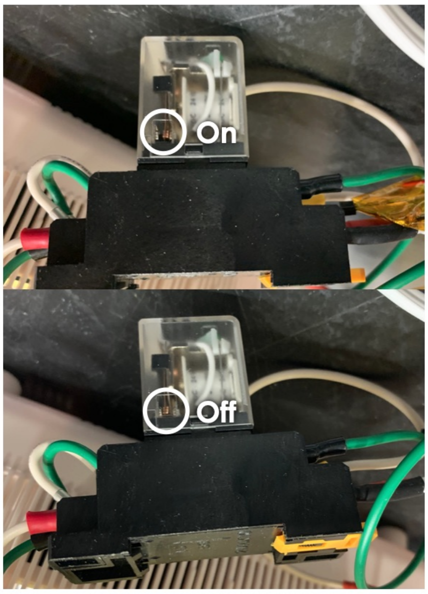




Figure 3.14 DPDT circuit and on/off modes

### Modification of the electric blanket

The operating voltage for the electric blanket is 110V AC, which is dangerous to handle with. And the length of the heating wire inside the blanket is about 19 meters. To make it safer and easier to cope with, I cut the wire into five pieces, four of which applied in the final prototype are 4.5 meters in length. There are two wires inside the silicone tube, one for heating and the other one for measurement. I wired both of them, red for heating wire and white for measuring wire.

2 `https://www.amazon.co.jp/-/en/gp/product/B08K34R8QB/ref=ppx_yo_dt_b_asin_title_o02_s00?ie=UTF8&psc=1`

### Calibration of temperature sensors from peltier device

There are three temperature sensors connected to the peltier device, one for the measurement of the temperature in the upper side of the peltier, one for the temperature in the bottom side of peltier and the rest one for the temperature of water flows beneath the bottom side of the peltier. The resistance values for these three temperature sensors are 9.35K ohm, 9.47k ohm and 9.40k ohm. Since the values are quite close, I only tested one sensor, the one measuring the water temperature, and assumed that their variations with the temperature were the same.

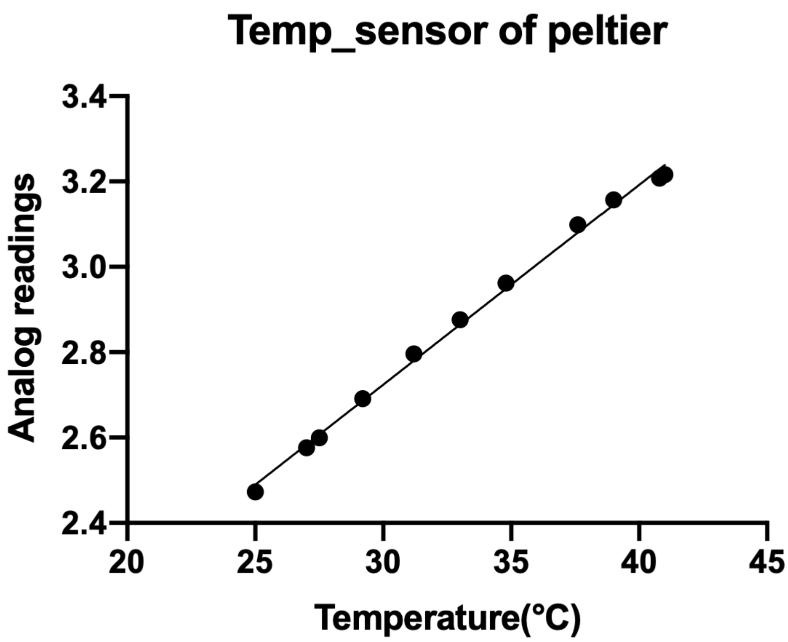



Figure 3.15 Diagram of the temperature sensor of peltier

The measurement took place in the tank of the device. I placed a thermometer above the testing point of the temperature sensor to get the temperature of the water. Then I added water with different temperatures into the tank and recorded the readings of voltage of the temperature sensor. Below is the diagram of the temperature sensor (Figure 3.15). Analog Readings (A) can be represented by a function of temperature (T) as follows:

$$A = 0.04683 * T + 1.319$$

### Calibration of temperature sensors for skin temperature

The model of the temperature sensor used here is KG-6143[3].The difference with the calibration of temperature sensors for skin temperature and that from peltier is that the one for skin temperature cannot get tested in water. So I borrowed the hot plate from Future Craft and used sugar as the heat transfer medium. Below is the diagram of the temperature sensor (Figure 3.16). Analog Readings (A) can be represented by a function of temperature (T) as follows:

$$A = 0.01875 * T - 0.03295$$

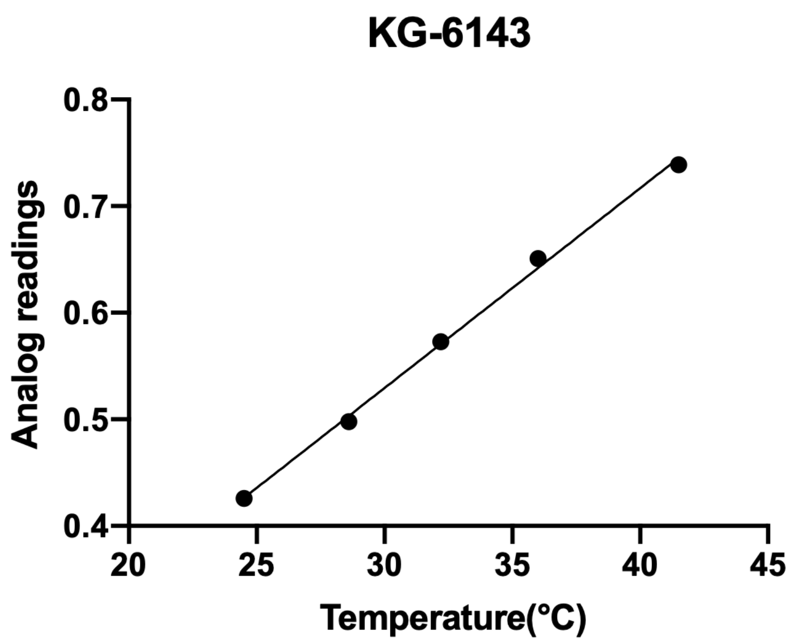



Figure 3.16 Diagram of the temperature sensor for skin temperature

3 https://www.ist-ag.com/sites/default/files/dttsic50x_e.pdf

### N-MOSFT switch

In order to control the on and off of the heating wires and DPDT relay, a switch that can be directly controlled by voltage output is required. Since the current of both the heating wires and relay is high and the voltage is 24V, I finally chose the MOSFET EKI04036[4]. I built two boards of switch with three MOSFET according to the circuit diagram. (Figure 3.17).

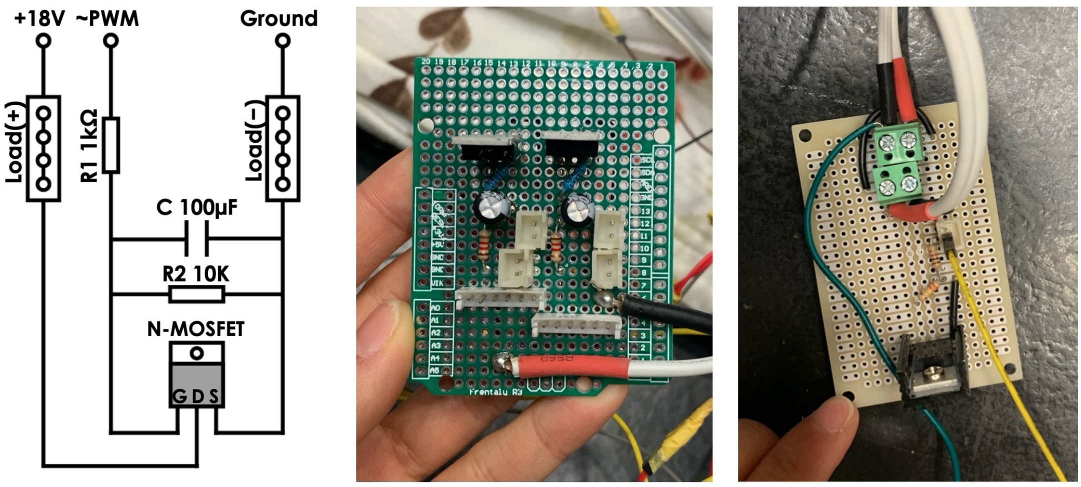



Figure 3.17 Mosfet circuit and two modules

The left board (in the middle of the figure) has two MOSFET switches to control the two zones of heating wires separately, connecting to the D3 and D4 of digital PWM pins in Arduino Mega 2560. While the right board in the figure is the MOSFET switch for DPDT relay and is connected to the D4 pin in the Mega board.

4 `https://akizukidenshi.com/download/ds/sanken/eki04036_ds_en.pdf`

### 3.4.4 Prototype design - Blanket main body

The blanket main body of my final prototype is still made by modification of the two blanket products mentioned above. I disassembled both the blanket parts and used the materials inside them to make my own blanket. There are mainly four layers in my blanket, the base layer to determine the location of the water pipes and heating wires, the layer of pipes and wires, the filler and the layer to fix the filler with the pipes and wires.

After considering the limitations of the sleep position detection system, I finally decided to make the blanket that separate two legs of the users so that the thermal distribution can still work quite well in different body parts without sleep position detection. Then the size of each part of the blanket would be very important. I measured people with height from 1.55m to 1.85m to collect the data listed below:

- The distance between two elbows with horizontal straight arms
- The vertical distance between shoulder to knee
- The vertical distance between knee to the ground
- The circumference of their shoes

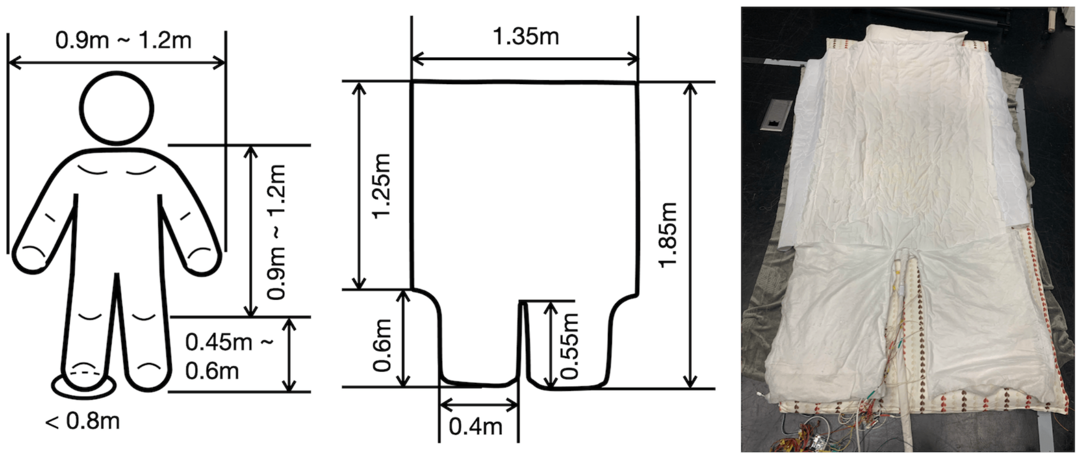



Figure 3.18 Size of the final blanket

Based on the data I gathered, the size of the final blanket prototype is: 185cm in height, 135cm in width, 55cm from the bottom bifurcation to bottom side (Figure 3.18). The water pipes would cover the upper body from shoulder and part of thighs, while the heating wire would cover the rest of thighs, area below the knee and part of arms, if the tester is around 1.7m in height. Below figure shows the arrangement of the pipes and wires (Figure 3.19). Zone 1 is the the place of water pipes and zone 2 and 3 are the heating wires.

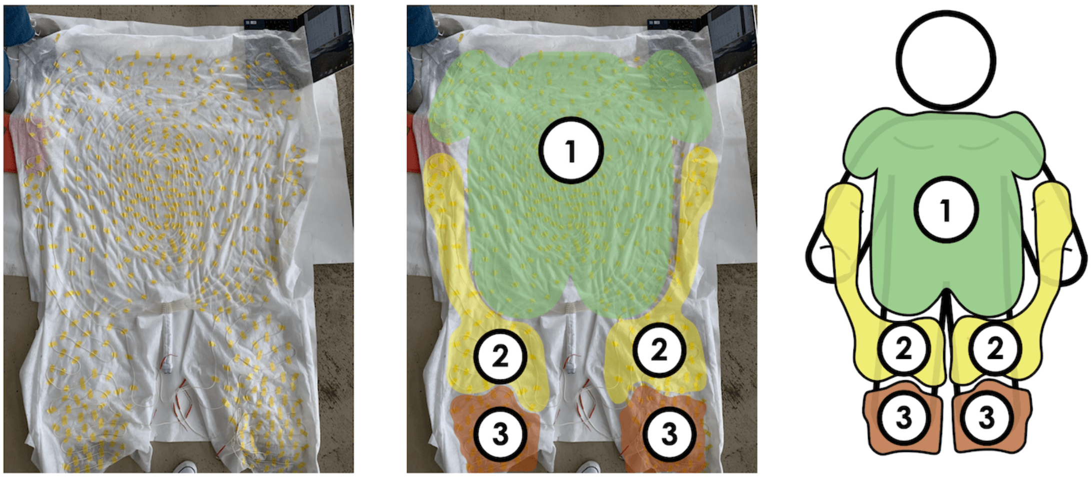



Figure 3.19 Arrangement of pipes(1) and wires(2,3)

There are also two IMU sensors placed on the upper side of the blanket to gather the times of the user changing the position. The distance between two IMU sensors is 60cm, which is decided as the distance between the shoulder and the crotch, two important parts determining the sleep position.

### 3.4.5 Prototype design - Control system

The microcontroller I chose for my final prototype is Arduino Mega 2560 as it has 16 analog input/output pins. The components and sensors that need to be controlled are three temperature sensors from peltier device(A0-A2), 12 temperature sensors for skin temperature measurement(A3-A14), two IMU sensors as sleep position monitor(SDA, SCL), two sets of heating wires(D3, D4) and the DPDT relay(D10) (Figure 3.20).

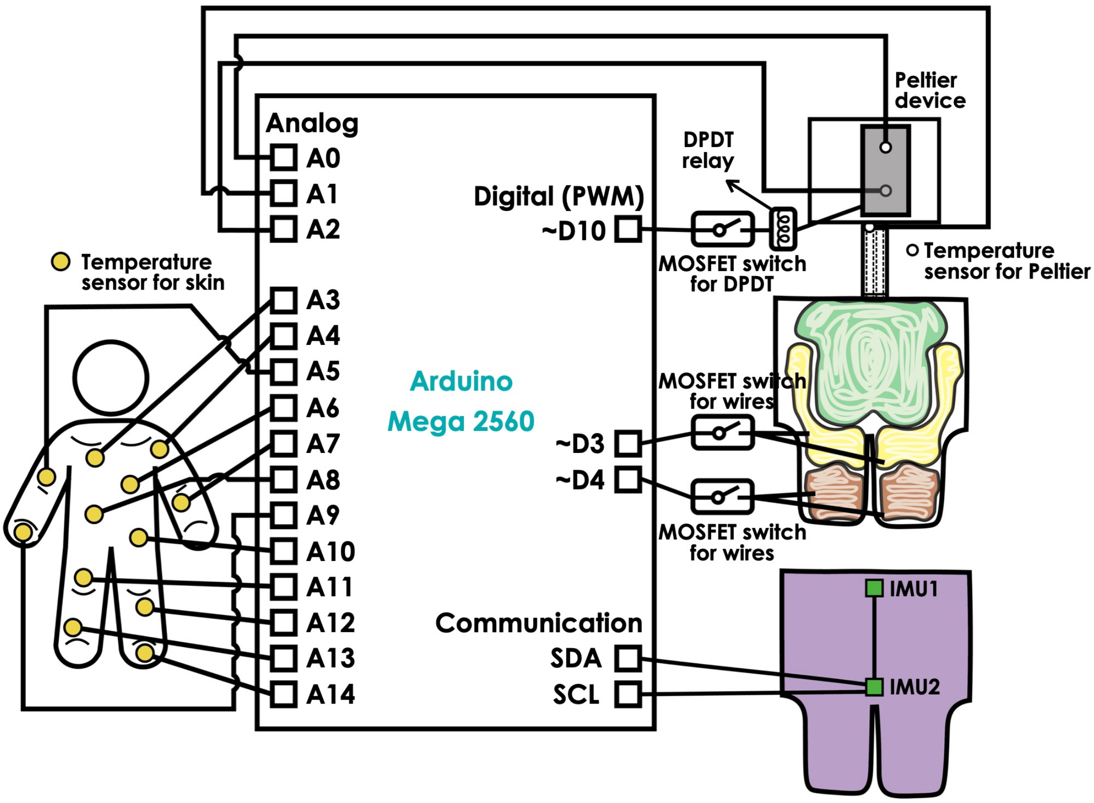



Figure 3.20 Arduino Mega 2560 and used pins

Besides the Arduino board, there are also two slide switches in the circuit board (Figure 3.12) to control the whole water heating/cooling system and the on/off of the peltier device. They would be turned on at the beginning of the test. Other sensors and components are all controlled by the Mega board. For the device part, the arduino gathers the data of the temperature on the top (A0) and bottom (A2) of the peltier device and the data of the water flowing into the pipes (A1). The temperature of the peltier (from 20°C to 45°C) is controlled by DPDT relay and MOSFET switch(D10). Another two heating zones inside the blanket are controlled by another two MOSFET switches separately (D3, D4). Two IMU sensors on the blanket surface report their data through pins SDA and SCL. Analog pins A3 to A14 are responsible for the collection of skin temperature of the testers. During the testing, All the analog reading pins (A0-A14), pin SDA and pin SCL send data through arduino to Matlab every five seconds. While three PWM digital pins (D3, D4 and D10) are modified in different time periods. In the first 20 minutes, the blanket is designed to help testers fall asleep easily. The peltier device would need to sustain the water temperature at about 25 to 27°C and two heating wires would need to keep the temperature around 43 to 45°C. In the middle of the testing (until 20 minutes before waking), the peltier device would keep the water temperature inside the pipes to be around 23 to 25°C and the heating wires stay the same. In the last period of testing (20 minutes before waking), the peltier device need to warm up the water temperature to around 40°C and two heating wires would be turned off.

# Chapter 4
# Proof of Concept

## 4.1. Pilot study

### 4.1.1 Overview

This pilot study was conducted to test the safety, feasibility and functionality of the final prototype. To be more detailed, I need to test the safety and functionality of the device, the comfort and heat distribution of the blanket, the feasibility of the temperature sensors and the operation of the system.

### 4.1.2 Test on device and blanket

The procedure and goal of the test is:

- Safety test: Check the states of the device after one and a half hour usage
- Functionality test: Check if all the components run normally and continuously in the one and a half hour
- Comfort test: Lie in the blanket and change sleep positions to see if the blanket is suitable for most of the sleep positions
- Heat distribution test: Check the temperature of the blanket under different settings

#### Safety test

The potential components that would have safety issues are two power supplies, the pump, the fan and the peltier. After continuously operating the device for one and a half hours, all of the components mentioned above work normally and were not overloaded or overheated.

### Functionality test

All the components function normally and continuously during the test.

### Comfort test

The blanket did not make the testers feel uncomfortable when lying in it. This blanket works best under the sleep on the back position and it suits for the sleep on the side position. But it cannot be used for the sleep on the stomach position.

### Heat distribution test

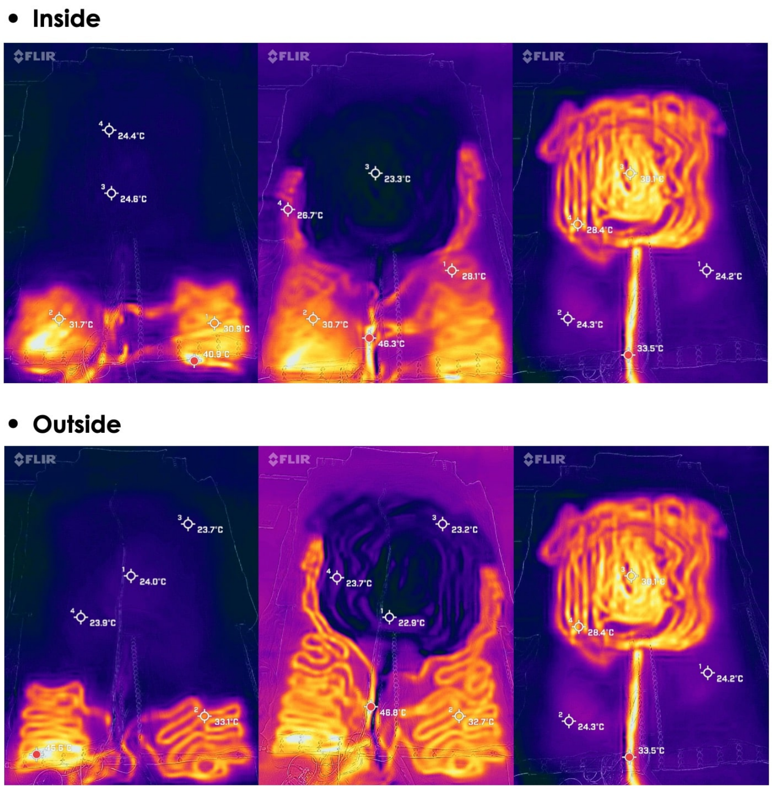



Figure 4.1 Infrared images of inside and outside of the blanket under three modes

Three modes were set for the test. They were peltier-off & Heat-D3-on, peltier-cold-on & Heat-D3-D4-on and peltier-hot-on & Heat-off. The infrared image for these three modes is shown below (Figure 4.1). Since the ambient temperature in the study room was quite low (about 22 centigrade), the difference between the peltier-off and peltier-cold-on was not very obvious.

### 4.1.3 Test on the temperature sensors

The temperature sensors were eventually decided to be attached directly to the skin using the medical adhesive bandage. To get a full-body thermal mapping image, twelve temperature sensors were the least amount. The locations to place the temperature sensors are shown left (Figure 4.2).

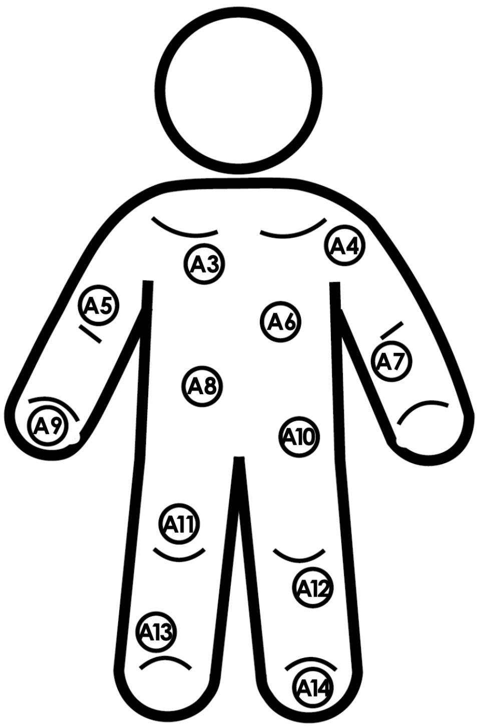



Figure 4.2 Planned placement

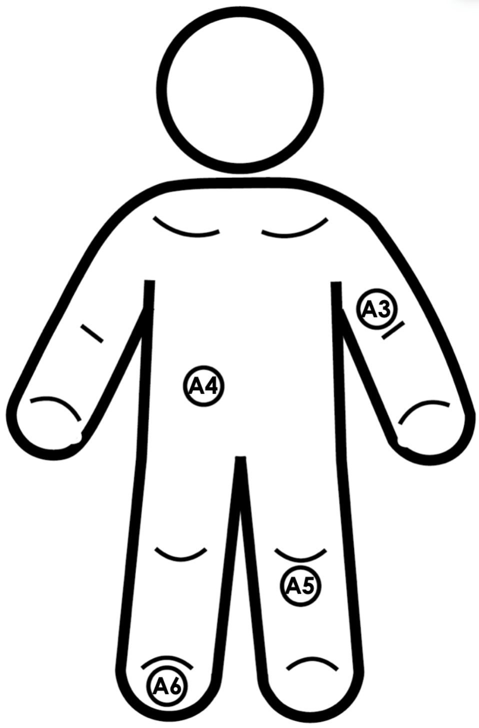



Figure 4.3 Actual placement

However, it would take about half an hour to attach all the temperature sensors to users and get them connected into the Arduino board, which is too long for users. And since each temperature sensor has three long wires for three pins, GND, signal and VDD, it is quite messy when they are all connected to the board (Figure 4.4). So, in the real user test, I only reserve four temperature sensors (Figure 4.3).

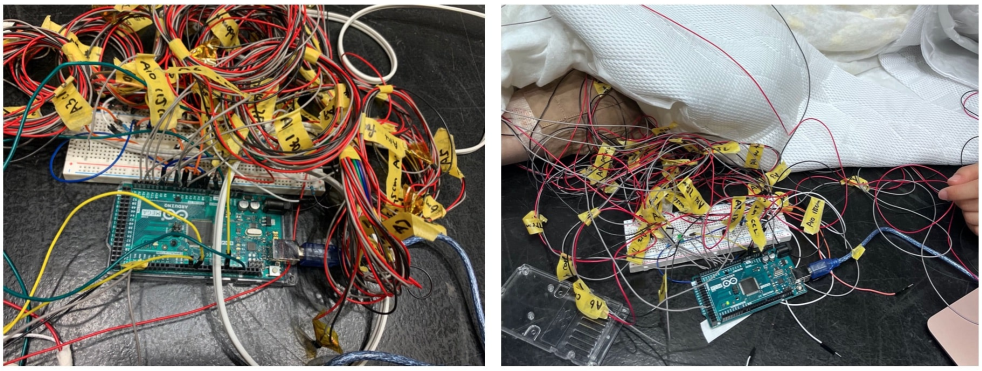


Figure 4.4 Messy wires

### 4.1.4 Test on the operation system

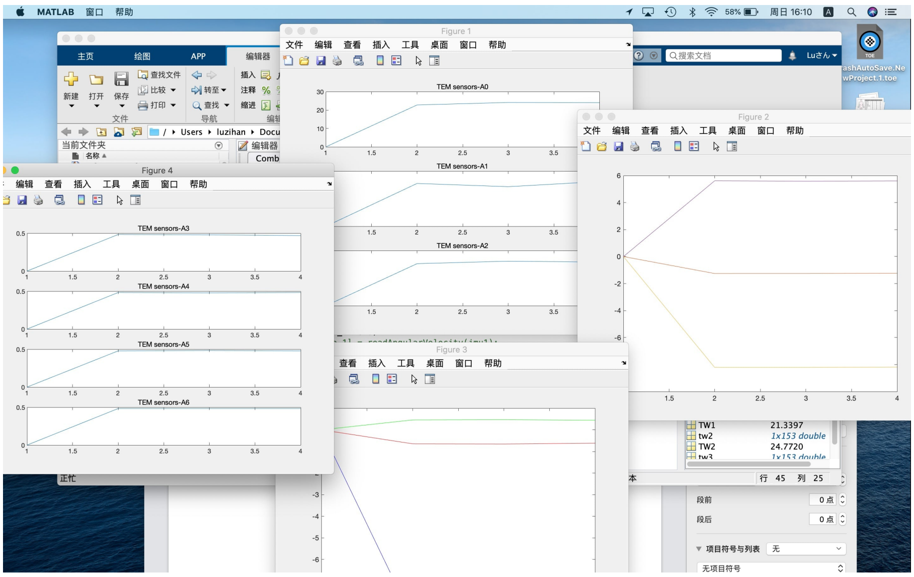



Figure 4.5 Matlab interface for data received by Arduino Mega2560

The system was run on the Matlab-R2020a using Arduino Mega 2560. Three types of data were collected during the operation of the system, three temperature data related to peltier devices(Figure 1 in Figure 4.5), four skin temperature data(Figure 4 in Figure 4.5) and acceleration states of two IMU sensors(Figure 2 & Figure 3 in Figure 4.5). Since the tester was only lying on the bed pad not actually falling asleep, the data gathered here did not contain useful information.

## 4.2. Sleep study

### 4.2.1 Overview

This study was conducted to evaluate the whole sleep experience, sleep and wake difficulty and sleep states. The sleep experience was assessed by both the feeling of the testers and the physiological data (HRV and EDA) during the whole sleep process. The sleep and wake difficulty were evaluated by the subjective feelings of the testers and the times of changing the positions. Sleep states were also estimated by the description of the testers and the variation of skin temperature.

The final prototype was designed for nocturnal sleep. However, due to the limitations in space and uncertainty of the safety of the prototype, the overnight sleep was replaced by a nap in the afternoon. Except for the form of sleep, other aspects of the test remained the same as designed.

In this study, eight participants (all born during 1990 to 1999, five female and three male, participant id from 1 to 10) were divided into two groups, six in the test group and four in the control group(participant 1 and 8 is the same person and participant 3 and 7 is the same person). The whole experiment lasted two hours for the control group and two and a half hours for the test group. Participants were asked to have a one-hour nap during the period of 1pm to 4pm lying in the sleep pad placed in the media studio booth room. All lights were closed during their nap. They were all asked to fill the questionnaire about their sleep[1] before the testing and participants in the test group were also required to fill the user

1 Sleep survey `https://docs.google.com/forms/d/e/1FAIpQLSckzWcrEeDtC1-2G-VmCPp-LKAKAsdJwJ-WQxk9Klu3bvg2-w/viewform?usp=sf_link`

satisfaction survey after the testing[2].

### 4.2.2 Study procedure

#### Set up

Half an hour before the test began, I would start to set up the experiment in the media studio. The set up process contained the placement of the bed pad and the pretest in Matlab of the blanket functions, which included the peltier device, two MOSFET switches, connections of each part, two IMU sensors and four skin temperature sensors (Figure 4.6).

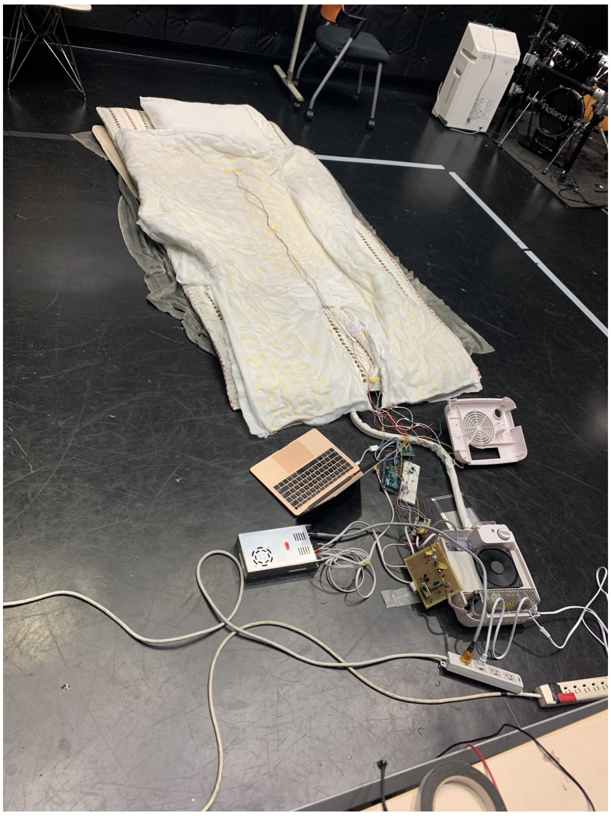


Figure 4.6 Set up for the experiment

2 User satisfaction survey https://docs.google.com/forms/d/e/1FAIpQLSdVka90s0Y_7J33pzurYlVwTamVrlLy0rT-f_kXogeB-RTERg/viewform?usp=sf_link

### Survey before sleep

After the participants came, they were asked to fill out a sleep survey and at the same time get familiar with the space and environment in the media studio as this place was quite isolated and the temperature of the air conditioner was quite low. The sleep survey could give a broad assessment of the sleep quality to help me understand their sleep states. The survey also contains questions about their nap, which would be very useful for the estimation of their nap experience.

### Cognition tests

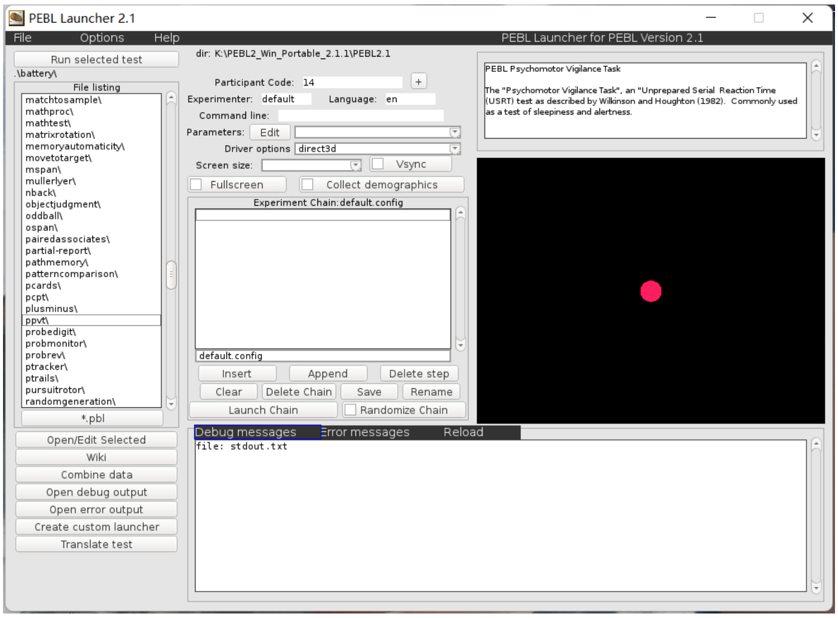



Figure 4.7 PEBL interface for PVT test

Two cognition tests, PVT test and hand-eye coordination test, are put here to measure the cognition improvement after a nap. The PVT test is responsible for alertness and hand-eye coordination is the reflection of attention, both of which would be improved after a high-quality nap. The platform of the PVT test for participants 1,2,4-6,8-10 is my iPhone on the website[3]. The total testing lasts for

3 http://www.sleepdisordersflorida.com/pvt1.html#responseOut

2 minutes and allows testers to have 22 to 25 attempts. The platform of PVT test for participant 3,7 is PEBL software in PC (Figure 4.7). The test in PEBL does not have a time limit, so the participant was asked to attempt 25 times.

The hand-eye coordination test was designed to ask the participant to stand two meters away from the wall and throw a table tennis ball to the wall with one hand and capture it with the other hand. The capture would not count if the ball fell into the ground. There were in total 50 times attempts and every five attempts, the participant was asked to switch hands(Figure 4.8).

Figure 4.8 Hand-eye coordination test

### Nap preparation

After two cognition tests, participants can have a ten-minute break to calm themselves down and at the same time, I would ask them more details about their answers of the sleep survey. Then the baseline of the physiological signals of participants were tested while they were lying in the blanket. The last step of the preparation was to attach four temperature sensors to the corresponding skin of the participants.

### Start nap

The process of napping was divided into three parts. In the first mode, the peltier device was not turned on as the environment temperature is low enough to decrease the skin temperature. Only the heating group below the middle of the calf was on to warm the feet of the participant. This part would last about 20 minutes. In the second mode, all the components were turned on. The peltier device was set as the cold mode. This part is designed to distance the temperature differences between core body and limbs to help participants stay asleep. This part was about 25 minutes. The last mode was designed to wake participants up and would last about 15 minutes as it was the time the water in the pipes reached the peak (Figure 4.9). Then if the participant was not awake, I would ask them to wake up.

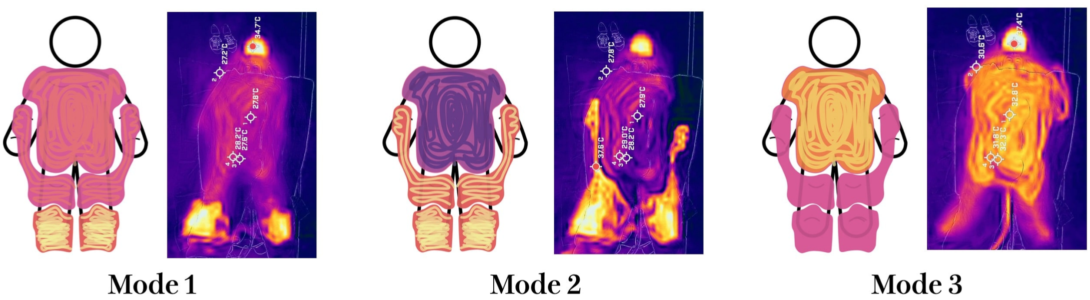



Figure 4.9 Three modes during napping experiment

### After nap

After the participant woke up from the nap, they could have a 5 to 10 minutes break before the two cognition tests. When the tests were done, they would need to fill the user satisfaction survey to report their sleep experience. I would also ask them some questions about their sleep states.

### 4.2.3 Result analysis

**Results of the sleep survey**

Table 4.1 Sleep survey result

| | **P1(P8)** | **P2** | **P3(P7)** | **P4** |
|---|---|---|---|---|
| **Gender** | F | M | F | M |
| **Sleep duration** | 8-9h | 7-8h | 6-7h | 7-8h |
| **Duration satisfaction** | Often | Often | Sometimes | Sometimes |
| **Sleep onset latency** | <30min | <10min | <10min | <30min |
| **Sleep position** | Back | Back | Side, Back | Back |
| **Night time wake** | <1/week | 1-2/week | Rare | 1-2/week |
| **Get up duration** | <10min | <10min | 10-30min | <10min |
| **Wake up mood** | Depends | Good | Depends | Bad |
| **Nap frequency** | 3-4/week | Rare | Never | 3-4/week |
| **Nap occur time** | 2-4pm | 2-4pm | - | 2-4pm |
| **Nap ends** | By alarm | By alarm | - | Naturally |
| **Caffeine intake** | <1/day | <1/day | >1/day | Rare |

| | **P5** | **P6** | **P9** | **P10** |
|---|---|---|---|---|
| **Gender** | F | M | F | F |
| **Sleep duration** | >9h | 7-8h | 6-7h | 7-8h |
| **Duration satisfaction** | Often | Often | Sometimes | Often |
| **Sleep onset latency** | <30min | <10min | <10min | <10min |
| **Sleep position** | Side | Any | Side, Back | Side |
| **Night time wake** | Rare | Rare | <1/week | >1/day |
| **Get up duration** | 10-30min | >30min | 10-30min | 10-30min |
| **Wake up mood** | Good | Depends | Depends | Good |
| **Nap frequency** | Never | 1-2/week | Rare | 3-4/week |
| **Nap occur time** | - | 8-10pm | 2-4pm | 11am-1pm |
| **Nap ends** | - | Naturally | By alarm | By alarm |
| **Caffeine intake** | >1/day | Rare | Rare | Rare |

The sleep survey mainly gathered two dimensions of information about all the participants, one is the overall picture of the nocturnal sleep and nap (Table 4.1) and the other is about their last night sleep(Table 4.2).

Table 4.2 States before experiment

| Participant ID | Sleep at | Wake at | With normal | Caffeine | Mood |
|---|---|---|---|---|---|
| Participant 1 | 1am | 8:50am | Less | Yes | Calm |
| Participant 2 | 1am | 8am | Nearly | No | Tense |
| Participant 3 | 3am | 9am | Nearly | No | Anxious |
| Participant 4 | 4am | 10:30am | Less | No | Calm |
| Participant 5 | 12am | 9am | Nearly | Yes | Calm |
| Participant 6 | 4:30am | 11:30am | Nearly | No | Happy |
| Participant 7 | 4:30am | 10am | Less | No | Upset |
| Participant 8 | 1am | 10am | Nearly | Yes | Upset |
| Participant 9 | 1am | 7am | Nearly | No | Calm |
| Participant 10 | 2am | 12:47pm | More | No | Calm |

From table 4.1, we could know that all the participants normally have a night sleep for more than 6 hours and none of them experience any kinds of sleep disorders. However, at the same time, all of them, more or less, still feel that they sometimes cannot get enough sleep. Some of them would supplement night sleep by napping during the day, but the others would not take a nap even when they feel sleepy because of the limited time, limited space, inappropriate situation, uncomfortable postures and terrible feelings after waking up from a nap.

### Results of cognition tests

The results of two cognition tests, PVT and hand-eye coordination test, are shown below respectively. (Table 4.3 for PVT test and Table 4.4 for hand-eye coordination test)

In the PVT test, the average of the test group is larger than that in the control group, which would, to some extent, indicate that people in the test group have a better improvement in their vigilance and alertness than the control group. If we have a closer look at the performance of each participant, it can be noticed that in both the test group and control group, half of the participants did not do better after napping, but the extent of doing worse in the test group is better than that in the control group. And the extent of doing better in the test group is better

Table 4.3 Result of PVT test

| | **Before sleep** | **After sleep** | **Difference** | **Increase(%)** |
|---|---|---|---|---|
| **Test group** | | | AVG:8.17 | AVG:1.94 |
| Participant 1 | 420 | 376 | 44 | 10.4 |
| Participant 2 | 424 | 424 | 0 | 0 |
| Participant 3 | 317 | 318 | -1 | -0.315 |
| Participant 4 | 420 | 406 | 14 | 3.33 |
| Participant 5 | 449 | 453 | -4 | -0.891 |
| Participant 6 | 417 | 421 | -4 | -0.959 |
| **Control group** | | | AVG:-18.8 | AVG:-4.40 |
| Participant 7 | 323 | 321 | 2 | 0.619 |
| Participant 8 | 461 | 486 | -25 | -5.42 |
| Participant 9 | 405 | 404 | 1 | 0.247 |
| Participant 10 | 407 | 460 | -53 | -13.0 |

Table 4.4 Result of hand-eye coordination test

| | **Before sleep** | **After sleep** | **Difference** | **Increase(%)** |
|---|---|---|---|---|
| **Test group** | - | - | AVG: 0.05 | AVG: 13 |
| Participant 1 | 0.42 | 0.58 | 0.16 | 38 |
| Participant 2 | 0.72 | 0.78 | 0.06 | 8 |
| Participant 3 | 0.26 | 0.3 | 0.04 | 15 |
| Participant 4 | 0.52 | 0.52 | 0 | 0 |
| Participant 5 | 0.26 | 0.32 | 0.06 | 23 |
| Participant 6 | 0.7 | 0.66 | -0.04 | -6 |
| **Control group** | - | - | AVG: 0.015 | AVG: 9 |
| Participant 7 | 0.26 | 0.34 | 0.08 | 31 |
| Participant 8 | 0.48 | 0.56 | 0.08 | 17 |
| Participant 9 | 0.76 | 0.66 | -0.1 | -13 |
| Participant 10 | 0.16 | 0.16 | 0 | 0 |

than that in the control group as well. Since participant 1 and 8 was the same person and participant 3 and 7 was the same person, their results of the PVT test also proved that my prototype could help to improve the cognition performance.

In the hand-eye coordination test, the average of the test group is also larger than that in the control group. Not like the PVT test, most of the participants performed better in hand-eye coordination after napping.

### Results related to sleep positions

There are two types of results related to the sleep positions of the participants, the first is the prototype tolerance for different positions and the second is the times of position changes during the test.

The previous survey result (Table 4.1) showed that most participants preferred sleep on the back or sleep on the side positions during their sleep. And the result obtained from the infrared camera (Figure 4.10) showed that the final prototype fitted quite well in the four different sleep positions that appeared during the test. But still, the prototype worked best in the sleep on the back position.

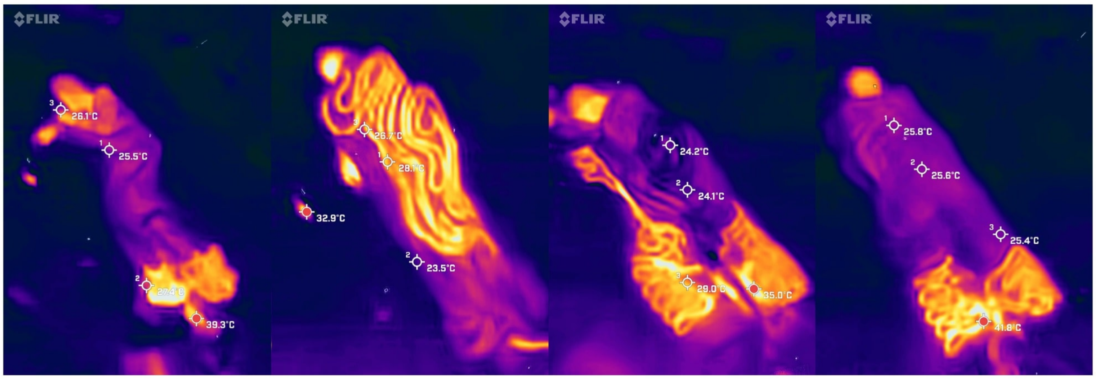



Figure 4.10 Result of fitness of different sleep positions

Two IMU sensors attached to the blanket recorded the times of participants changing their positions during the test in both control group and test group. The average times of position changes in two groups during different periods were calculated and shown as below (Figure 4.11). Each period corresponded to each part in the experiment process. It is shown in the figure that during the first 20 minutes, participants in the control group would change their sleep positions more frequently than the test group. But in the second 25 minutes, the result is the opposite. The sum of changes in the two groups are almost the same. This result might indicate that the final prototype could help participants to fall asleep more smoothly.

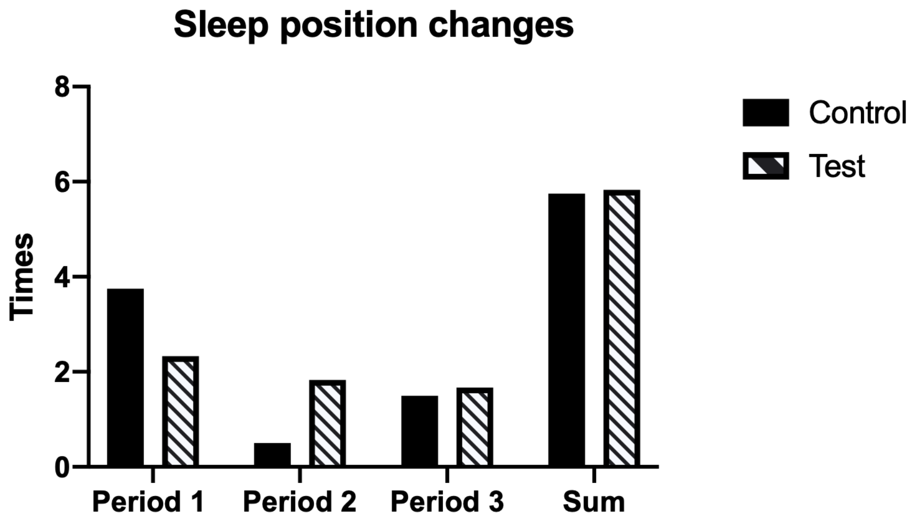



Figure 4.11 Result of sleep position changes

#### Results related to temperature changes

Temperature sensors of the peltier device record the temperature changes during the three periods of sleep test. The result is shown below. 'TEM sensors-A0' and 'TEM sensors-A2' measured the upper side and the bottom side of the peltier separately, while 'TEM sensors-A1' was responsible for the temperature of the water altered by the peltier. The water temperature in the first period was maintained at around 22°C, the same as the environment temperature. The water temperature would also rise a little bit as the result of the heat exchange with the core body. In the second period, the peltier device began to turn down the water temperature to about 18°C and it could be lower if time allowed. In the third period, the water temperature would rise up to warm the core body to prepare for the wake. The water temperature would reach around 45°C at the end of this period (Figure 4.12(The framed data is the temperature of the water flowing into the blanket)).

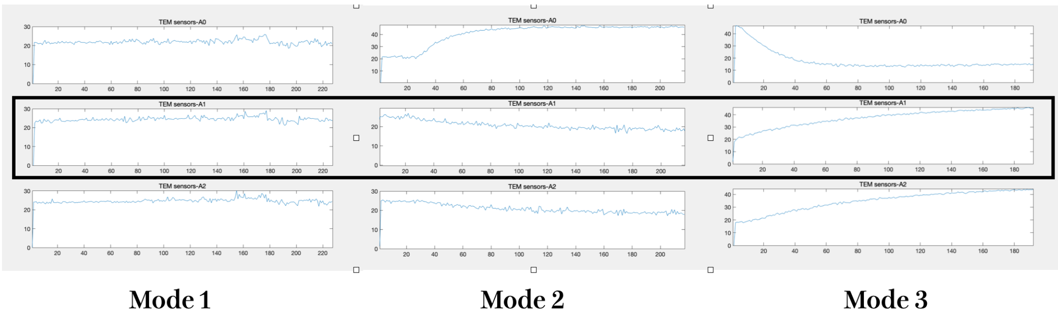



Figure 4.12 Result of temperature sensors of peltier

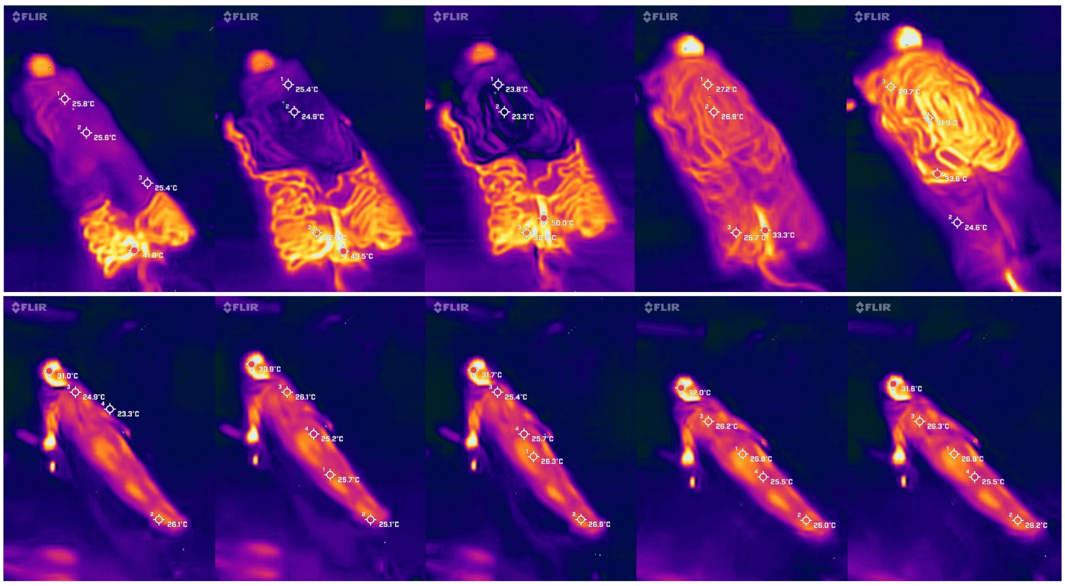


Figure 4.13 Result of temperature variation of the prototype blanket (top) and normal blanket (bottom)

However, the actual temperature of water flowing in the pipe inside the blanket was not the same as the water in the water tank below the peltier device. The actual temperature distribution inside the blanket was recorded with the help of an infrared camera. Besides the temperature variation of the test group, the result of the control group using a normal blanket is also displayed below (Figure 4.13). The top row shows the temperature variation of the prototype blanket during experiment in roughly 12 minutes, while bottom row is the temperature of the normal blanket during napping in 12 minutes.

Another temperature-related result is from four skin temperature sensors. However, for all the participants either in the test group or control group, there is no discernible difference during the napping process. So I picked the data of one participant from the test group (Figure 4.14) and another one participant from the control group (Figure 4.15) to present the result. 'TEM sensors-A3' measured the skin temperature above the left elbow; 'TEM sensors-A4' measured the skin temperature of abdomen; 'TEM sensors-A5' measured the skin temperature below the right knee; 'TEM sensors-A6' measured the skin temperature of left foot.

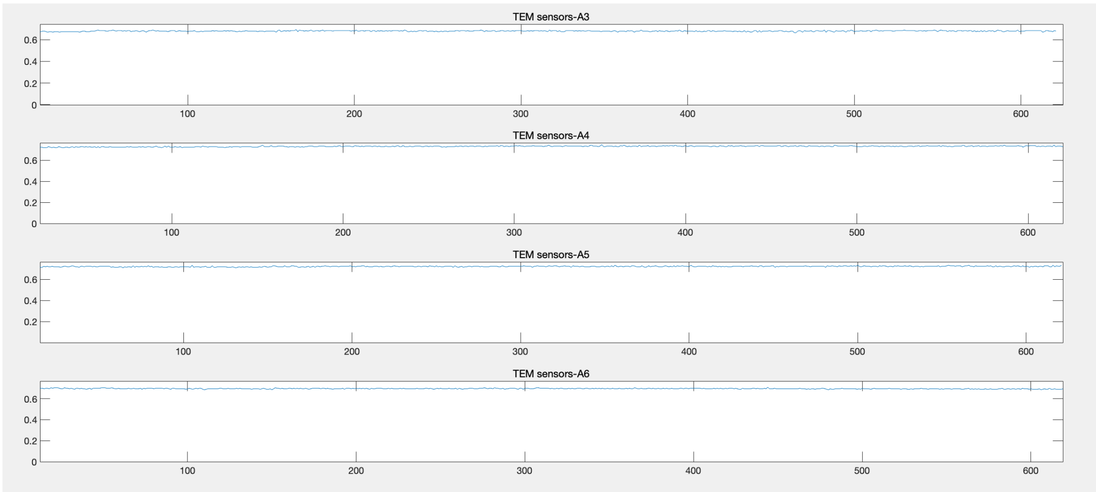
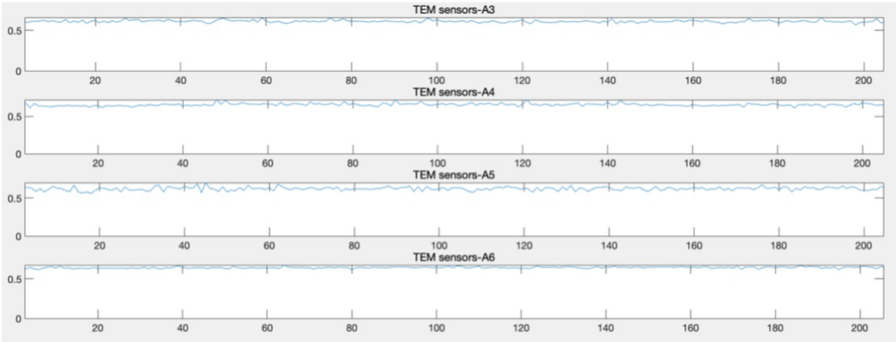
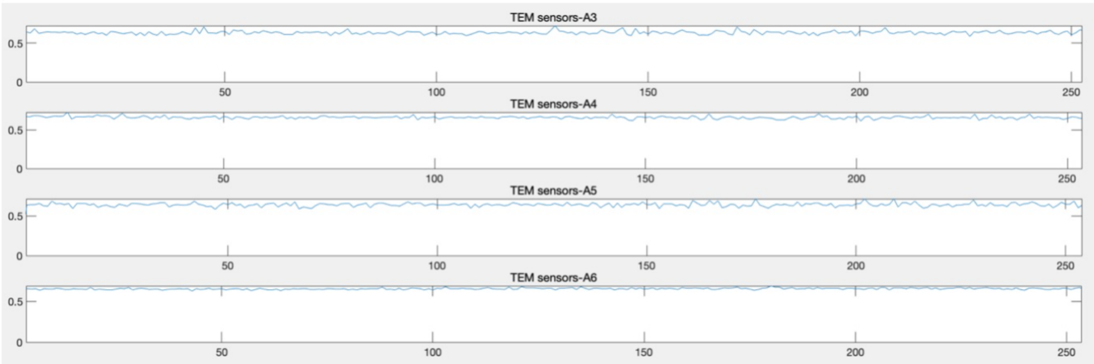



Figure 4.14 Result of skin temperature variation in the control group (60min)

- **Mode 1（20min）**




- **Mode 2（25min）**




- **Mode 3（15min）**

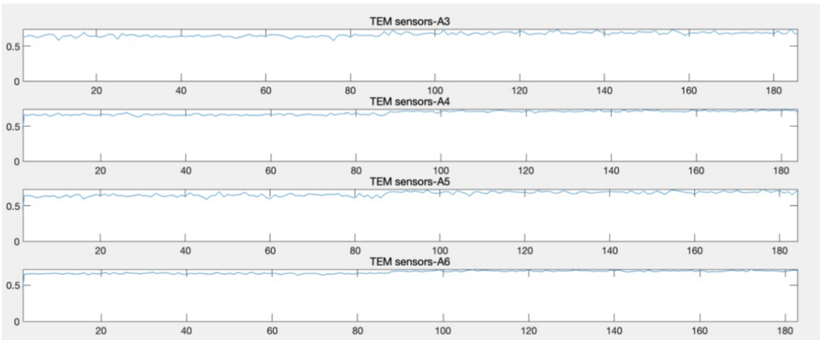



Figure 4.15 Result of skin temperature variation in the test group

### Result of user satisfaction survey

The user satisfaction survey covered three aspects, the overall rating for the system, the comparison with normal naps and the uncomfortable factors (Table 4.5). For the overall rating, score 1 means 'absolutely no' and score 7 means 'absolutely yes'. In the comparison part, for the 'Distinction level', the score 1 means 'same' and score 7 means 'totally different' ; for 'Nap time duration', score 1 means 'Too short' and score 7 means 'Too long'; while for the rest two, score 1 means 'absolutely no' and score 7 means 'absolutely yes'. For the uncomfortable factors, score 1 means 'not uncomfortable' and score 7 means 'very comfortable'.

Table 4.5 Result of user satisfaction survey

| | **P1** | **P2** | **P3** | **P4** | **P5** | **P6** | **AVG** |
|---|---|---|---|---|---|---|---|
| **Experience satisfaction** | 7 | 7 | 6 | 5 | 6 | 7 | 6.3 |
| **Preferred usage frequency** | 7 | 6 | 6 | 6 | 6 | 6 | 6.2 |
| **System and experiment settings** | | | | | | | |
| System over twisted | 4 | 4 | 3 | 2 | 2 | 1 | 2.7 |
| System integration | 4 | 4 | 5 | 6 | 4 | 6 | 4.8 |
| Preparation too long | 2 | 2 | 3 | 4 | 2 | 2 | 2.5 |
| **Compare with normal nap** | | | | | | | |
| Distinction level | 3 | 3 | 3 | 5 | 6 | 4 | 4.0 |
| Nap time duration | 3 | 2 | 3 | 4 | 6 | 3 | 3.5 |
| Fall asleep easily | 7 | 5 | 4 | 4 | 6 | 6 | 5.3 |
| Wake up easily | 5 | 6 | 6 | 6 | 7 | 5 | 5.8 |
| **Discomfort level** | | | | | | | |
| Machine noise | 1 | 1 | 2 | 1 | 1 | 1 | 1.2 |
| Environemnt | 1 | 2 | 2 | 1 | 3 | 6 | 2.5 |
| Blanket itself | 2 | 1 | 2 | 1 | 3 | 1 | 1.7 |
| Thermal output | 1 | 2 | 3 | 1 | 2 | 1 | 1.7 |
| Temperature sensors | 2 | 2 | 3 | 5 | 3 | 1 | 2.7 |
| BVP-GSR sensor | 3 | 3 | 4 | 3 | 7 | 3 | 3.8 |

All the participants gave a high score in both the experience satisfaction and the preferred usage frequency as all of them fell asleep in the experiment and woke up with a nice mood. The preferred usage frequency is referred to the prototype (or product) without any attached sensors in the human body, including the skin temperature sensors and physiological sensors. And the scores for the unnecessary complexity and system integration are also the result of these sensors. The preparation time for participants in the control group was about 20 minutes to half an hour but not included the time for cognition tests.

Compared with normal napping, the participants told me that the differences mostly came from the experience environment, attached sensors and also the presence of operators. Napping for one hour is short for some participants and too long for other participants but it seems to be a quite balanced duration. The survey result for sleep and wake easiness also showed that participants agreed that this prototype can help improve their napping quality.Two of the participants (both male) woke up automatically at the end of the test, which was beyond their expectations.

In the assessment of the discomfort level, machine noise, blanket itself and thermal output of the blanket did not bring much uncomfortable feelings to the participants. Some participants mentioned that they felt very pleased about the thermal output, especially the warmth on feet in the first period and the warmth on core body in the last period. The environment made participant 6 feel very uncomfortable as he normally cannot fall into sleep when there is an acquaintance around. But he still fell asleep in the experiment so he scored high for the whole system. Two types of sensors were the two biggest sources that made participants feel uncomfortable. Some participants mentioned that they could feel the pull from the wires of temperature sensors when they were about to change their sleep positions, which would affect their sleep experience. And the BVP-GSR sensor placed on their fingers also stopped them from changing their positions.

### 4.2.4 Discussion

The result of the sleep study manifests that the final prototype could help participants improve their nap quality in cognition performance, emotions and easiness to fall asleep and wake up. But there still remains some problems regarding experiment settings and could have some space for the improvement of the whole system.

The first problem is about the participants. I invited eight participants and two of them took part in both the test group and the control group, so I have ten sets of data, six from the test group and four from the control group. But for a sleep study, ten is too limited to get the statistically significant data. Besides, for the test group, the number of female and male participants were the same, but for the control group, there were only female participants. Participant gender distribution would impact the final results. Another problem related to the participants is that no matter in the test group or control group, there were half of them never or rarely napping. This napping experiment might influence their nocturnal sleep rhythm.

The second problem is about the cognition tests. In the experiment, the participants were required to have two cognition tests on alertness and attention. Yet, napping for only 20 minutes is able to improve these two cognition performances. I should have included some cognition tests on the learning and memory, which would be recovered from the 60-min naps, to compare the sleep quality in a more broader way.

The third problem is about the temperature sensor for skin. The sensor I used measures the contact temperature with both sides of the sensor. But when it was applied for the skin temperature measurement, only one side of it can touch the skin, which would make the result to be very inaccurate and at the same time, not accordant with the calibrated results. So in the actual testing, I only recorded the raw analog data of the temperature sensors to see the trend of variation. And the result showed that there is not significant variation in skin temperature, which could be caused by the wrong usage of the sensors.

When it comes to the possible improvements, the first is regarding the thermal mapping system that was considered in the concept design but not able to be accomplished. It was designed to reflect the skin temperatures of different body parts for future interactions during sleep. However, due to the limitations of the sensors and technology, this function was not realized in the final experiment. Besides, as participants were asked to take naps in the experiment, the variations of their skin temperature were not that obvious compared with the nocturnal sleep. Therefore, in the future, if comfort factors are taken into account, the sensors should be applied on the surface of the blanket rather than attached to the skin.

To achieve this, the data of the correlation of skin temperature and temperature of different clothes covered on the skin need to be gathered and analyzed to make sure that the thermal mapping result is accorded with the actual skin temperature distribution.

The second improvement is regarding the thermal output. In the final prototype, only the one part can give both cool and heat output. This works well if the ambient temperature is between 20 to 25 centigrade. Yet, if this blanket is designed as the blanket that can be used during the whole year, regardless of the ambient environment, the thermal output of each part should be re-designed to fit different needs. Apart from that, the final blanket prototype was also designed in a strange shape to make sure it can stand different sleep postures. In the future, this special design should also be removed to improve the comfort. As a result, the thermal output needs to be modified to make sure it can still work well under different sleep positions.

Last but not least, to better improve the sleep quality, attempts of adjusting the thermal outputs of different parts could be made to influence the duration of different sleep stages to help users to maximize the benefits of sleep. The distinction of different sleep stages can be estimated by physiological signals like EEG and EOG.

# Chapter 5
# Conclusion

This research was intended to explore a new temperature-related system that provides different thermal outputs by body parts to improve sleep quality. The choice of temperature as the focus of the research is based on the easy manipulation, extensive and long-term impacts and possibility of interactions. Since temperature is categorized as the environmental factor that influences sleep quality, it can be controlled more simply than other three types of influencing factors, physiological factors, psychological factors, family and social factors. Temperature has also been proved to play different roles in different stages of sleep. As temperature sensors are everywhere in the skin and sensors in different body parts may convey different messages, applying different types of thermal outputs in different locations of the human body would have various influences and get diverse feedback.

Based on the relationship between temperature and sleep, I built a blanket prototype called RhythmSleep to give different thermal outputs by body parts and by sleep states to improve sleep quality. There has already been some research on this topic, but they focused only on one aspect in the microclimate either by changing the ambient temperature to the same centigrade for the whole body or changing skin temperature of one body part. What I did in this research was to take the human body as a more complex system under the influence of temperature and to combine different aspects that temperature might have to amplify the extent of improvement in sleep quality. The biology support behind my design concept is that there are at least two brain structures, parietal lobe and hypothalamus, that are proven to process and regulate temperature-related information of the human body. This information could be skin temperature, core body temperature or organ temperatures. And in most cases, other researchers only consider one pathway, the pathway of core body temperature guided by hypothalamus, for their studies. I want to see that under a more complex and comparatively precise temperature regulation, how sleep quality could be modified.

The result of my nap experiment showed that the final prototype was able to improve the sleep quality both objectively and subjectively. The objective evaluations contained two cognition tests, change times of sleep positions and skin temperature variations. Some of the results indicated that the sleep quality of testers had been improved compared with control groups and the other results did not have obvious distinctions with control groups. The subjective evaluation was mainly the feelings after waking up and the preference of long-term usage. All testers gave high scores on their sleep experience and my prototype. Most of them believed that it is easier to fall asleep and wake up using my prototype compared with normal napping. However, as the number of participants in the experiment is still too limited compared with normal sleep experiments (more than 50 participants), more data are needed to get a more solid conclusion.

Aside from the limitations on the amount of data, other works regarding the thermal system and experiment content can be improved for future studies. In the current prototype, only the part corresponding to the main body could give both cool and heat output. To make sure the blanket can suit any seasons and any sleep positions, the thermal part needs to be rearranged. For the experiment content, more evaluation methods are needed to get the multi-dimensional analysis on the improvement of sleep quality in the objective manner. Besides, it would be better if naps can be replaced by overnight sleep.

To sum up, this research attempted to develop a new method of distributing different thermal outputs to different body parts to improve sleep quality. And the final prototype indicated that by applying different thermal modes by body parts and by sleep states was able to improve the nap quality. This research is a small step to seek more possibilities on the multi-dimensional influences of ambient temperature on sleep as the former research emphasized the effects of temperature in one dimension. And the result suggested that this multi-dimensional method was feasible, effective and worth exploring more.

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