ORIGINAL ARTICLE

Evaluation of Sleeping Comfort of Bed Mattresses with Different Elastic Moduli for Each Body Region

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Abstract: The purpose of this study is to evaluate sleep comfort of bed mattresses with different elastic moduli for each body region by measuring physiological and psychological responses. We measured the blood flow of the biceps femoris using near-infrared spectroscopy (NIRS) from the viewpoint of hemodynamics and shape of the back in a supine posture when a person is lying on mattresses with different elastic moduli for each body region. Conventional sleep evaluations were performed to record physiological responses during sleep by polysomnographs (PSG) and actigraphs. Psychological responses during sleep were also evaluated by using the profile of mood states (POMS) test. The results from NIRS revealed that intramuscular metabolic reaction is different according to the sleep posture. Sleep evaluations by PSG and actigraphs showed no significant differences between these mattresses, whereas significant differences were found in the POMS test between some of them. We surmised that difference in hemodynamics is one of the factors in sleep comfort that changes the mood after getting up.

Keywords: *Sleeping comfort, Physiological and psychological response measurements, Shape measurement*

1. INTRODUCTION

Sleep is essential in maintaining body condition. For a person to have a restful sleep, it is important that a good sleeping environment is provided. One factor that affects the sleeping environment is bedding, which includes futons, bed mattress (hereinafter, “mattresses”), blankets, towel blankets, sheets, pillows, and nightwear. Because bedding is used for many hours in direct contact with people, it is believed to exert a significant impact on sleep. One of the most important types of bedding is mattresses, since they support a sleeping person’s body while ensuring comfortable sleep.

There are several studies about the relationship between mattresses and sleeping comfort [1-5]. For example, we revealed that comfort was better in mattresses of high elastic modulus [6]. Recently, there are mattresses with different elastic moduli for each body region in the market [7]. However, selection of a mattress is dependent on individual subjectivity [8]. Indeed, objective criteria to assess comfortable sleeping on mattresses have not been established. The factors of mattresses that affect comfortable sleeping should be clarified.

As a method of further improving the sleep comfort, we focused on mattresses with different elastic moduli for each body region. When a person is lying down, it is

reported that the proportion by weight of each part is different. We postulated that good comfort can be obtained in a sleeping posture corresponding to the weight fraction of the body.

The purpose of this study is to evaluate sleep comfort of mattresses with different elastic moduli for each body region by measuring physiological and psychological responses. It is assumed that differences in mattresses affect physio-psychological responses. For example, the study has been reported that the poor circulation causes a general malaise [9]. We predict that sleep comfort is changed by the impact of sleep posture on hemodynamics. Therefore, we carried out three experiments. For the first, it is thought that variations of the elastic properties of a mattress affect sleeping postures, which presumably cause differences in the feel of mattresses. We measured the shape of the back in a supine posture when a person is lying on a mattress. For the second, we assumed that the differences of mattresses affect the circulation state of muscles. We evaluated the effects of mattresses on hemodynamics of lying subjects by measuring the blood flow of the biceps femoris using NIRS. For the third, using mattresses with different elastic moduli for each body region, we estimated the physio-psychological responses during sleep by actigraphs and PSG as conventional sleep evaluation methods, and the mood survey by the POMS test.

Table 1: Subject physique data

Number of subjects	5
Height (cm)	173.8±4.8
Weight (kg)	63.8±6.2
BMI	21.1±1.1

Table 2: Subject physique data

Number of subjects	5
Height (cm)	172.8±3.3
Weight (kg)	59.7±4.6
BMI	20.0±0.9

2. METHOD

2.1 Subject

The feelings of humans evoked by a mattress may differ depending on their gender, age, and physique. It was therefore decided to limit the subjects of this research to male individuals with a standard physique, whose Body Mass Index (BMI) as computed by weight/height^2 fell within the range of 18.5 – 25. The subjects were 5 male university students who were healthy and had no sleep disorders. Tables 1 and 2 show data on their physiques. Table 1 shows the subjects that slept on the mattresses with different elastic moduli in each region. Table 2 shows the subjects that slept on mattresses of uniform moduli. The subjects were instructed beforehand not to consume any coffee, alcohol, etc. or do any excessive exercise prior to the experiment. They were also asked to wear the specified clothing while sleeping. Before the day of the experiment, the subjects submitted a written agreement on their participation in the experiment and use of the experimental data for subsequent investigations. Experiments for this research were conducted with the approval of Shinshu University's Ethical Committee for Research on Humans.

2.2 Experimental environment and samples

The experiment was conducted in a thermohygrostatic room where constant temperature and humidity of 25°C and 50% RH were maintained. The experimental environment was kept in a thermally comfortable condition. Mattresses of the pocket coil type were used as experimental samples. The pocket coil specifications of each type of mattress are shown in Table 3. The spring constant was obtained through our experiment of elasticity. In this study, we prepared five mattress samples composed from three types of the pocket coils that are used in commer-

Table 3: Spring constants of mattress pocket coils

Sample	Spring constant (kgf/mm)
A	0.0140
B	0.0100
C	0.0072

cially available mattress. The five types of mattresses are called as “ABAB”, “AAAA”, “BBBB”, “BBCB”, and “BCBB” in descending order according to their elasticity. The alphabet of four characters sequentially shows the 4 parts of body from left: the head, chest, waist, and leg portions.

Samples used were three-quarter beds that are commonly available. The regions were 30cm, 40cm, 40cm, and 75 cm respectively from the head.

Other than mattresses, bed pads (outer fabric: 100% cotton; padding: 100% polyester), sheets (100% cotton), towel blankets (100% cotton), and pillows (outer fabric: 75% cotton/25% polyester; padding: 100% polyester) were used.

2.3 Measurement of body subduction when lying on a mattress

It is considered that variations of the elastic properties in a mattress presumably affect sleep postures. The most common posture at the time of falling asleep and during sleep is a supine position [10]. Therefore, we measured body subduction of when a person is lying on mattress.

The curve of the back of the human body on the median line was measured while lying in the supine position by using the shape tape (Measureland Co. Inc.). The subjects are shown in Table 1. Each subject lay on 5 different mattresses with random sequence. For each subject, the experiment was repeated 5 times using each type of mattress. We used the average values of the five subjects as the data.

2.4 Muscle blood flow

We attempted to understand the hemodynamics of muscles when a person is lying on a mattress. We focused on hemodynamics in the biceps femoris muscle as a factor to affect sleep. The blood flows of the biceps femoris lying on different types of mattresses were evaluated by NIRS. NIRS outputs 3 indicators: oxyhemoglobin (OxyHb), deoxyhemoglobin (DeoxyHb) and total hemoglobin (TotalHb). This measurement is intended to determine the differences in muscle metabolism when a person is lying on a mattress by using these indicators.

Figure 1: Measurement channels

We arranged detection probes and near-infrared light illumination probes in a grid every 3cm. And blood flow was measured at the same time for 4ch (shown in Figure 1). We measured 3 indicators for 4 channels by 25Hz sampling frequency. The subjects were 3 healthy male students of standard proportions (height: 168.7 ± 1.5 cm; weight 57.3 ± 5.0 kg). The subjects lay on 3 different mattresses randomly to avoid the order effect. Experimental environment was 25°C 50% RH.

In this experimental procedure, after attaching the measurement probes of NIRS to the subject's leg, we carried out the control measurement of blood flow in the prone position for 10 minutes. And then, we measured in the supine position lying for 30 minutes. Subjects were instructed to remain as still as possible. Analysis was calculated by interval average per minute for measured data for 30 min in the supine position. The average values of CH.1 and CH.4 along the muscle fibers (shown in Figure 1) were used as the results. The measured values were indicated as relative values on the basis of the prone position.

Note that it took three days to collect the data of three kinds of samples for each subject. In order to reduce the influence of the physical state by life time period, measurements were performed in the same time period.

2.5 Experimental procedure of sleep experiment

The experiment was performed according to the subjects' usual times for going to bed and waking up whenever possible. Subjects entered the laboratory one hour before their bedtime. After being briefed on the experiment, the actigraph and electrodes for recording PSG were installed, pre-sleep surveys were conducted, and POMS test rating was performed to check their mood prior to sleep. They were then asked to assume a supine position on a mattress, and the electrodes' lead wires were connected to the measuring instruments. Consideration was given to keep the impedance of electrodes below $5\text{ k}\Omega$.

After checking the recording conditions, the experiment was started by turning off the lights. The experiment was assumed to have ended when the lights of the room were

turned on and the subjects had woken up and risen from the mattress. Then, electrodes were removed and post-waking surveys and POMS test ratings immediately after sleep were performed.

Each subject lay on 5 different mattresses with random sequence. For each subject, the experiment was repeated 2 times using each type of mattress.

2.6 Polysomnograph (PSG)

We carried out subjective and qualitative evaluation of the effects on sleep of mattress with different degrees of elasticity using PSG. PSG records human sleep-related physiological phenomena to monitor the depth and development of sleep over time, and necessitates simultaneous recording of multiple physiological indices (electroencephalogram (EEG), electrooculogram (EOG), and electromyography (EMG)) [11].

In accordance with the international ten-twenty electrode system, the EEG was recorded by using a monopolar lead method with C3, C4, and A1 and A2 (left and right ear lobes) being standard references. For the EOG, eye movements on both sides were recorded by installing electrodes at an area 1 cm obliquely upward from the outer canthus of the left eye and at an area 1 cm obliquely downward from the outer canthus of the right eye, and by using a monopolar lead method in which the lobes of ears (A1, A2) served as reference electrodes. To record the EMG of the mentalis muscle, two electrodes were attached 3-4 cm apart from each other above the mentalis muscle and recording was made using a bipolar lead method. Grounding of the body was made in the region near the collarbone. Figure 2 illustrates where the electrodes were attached. The electrodes used for this experiment were disc biological electrodes (ACT biological electrodes AC-P102, Digitex Lab. Co., Ltd.), to which paste for measuring biological signals was applied. To prevent the electrodes from peeling off, elastic surgical tape was attached over the electrodes. The biological signals were amplified using a bio-amplifier (Polymate AP1132, TEAC Corporation) and then converted from analog to digital at a sampling frequency of 500 Hz before being

Figure 2: Electrode attachment areas

recorded on a computer.

Sleep stages, which indicate the depth of sleep, were determined from the collected PSG data. Analysis was made for a three-hour period from the start of the experiment, since we have assumed that sleep can be deepest during the first cycle and that the condition of sleep during the initial stage from going to bed to falling asleep can most significantly affect sleep feelings. Additionally, variance of data obtained among subjects would be small. The depth of sleep can be determined in a comprehensive calculus based on the occurrence ratio of brain waves in each band, amplitudes, eye movements, and mentalis muscle activity.

Sleep stages were recorded every 30 seconds using sleep analysis software (Sleep Sign Ver. 2, Kissei Comtec Co., Ltd.) and determined in accordance with the international scoring system of Rechtschaffen and Kales [12]. Sleep efficiency and occurrence ratios of each sleep stage during the respective analysis periods were then computed based on the results. Also, sleep conditions were compared among different samples by calculating the average sleep depth and sleep efficiency. The average sleep depth is an index indicating the depth of sleep per unit time [6]. The average sleep depth S is defined by

$$S = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

Where n is the total number of section ($N=360$) in a given analysis period and x_i is the sleep stage that has appeared. For chronological data of sleep stages (indicating sleep depth) appearing in a given analysis period, a score of 0 was assigned to Stage W (including MT), with 0.5 assigned to Stage REM, 1 to Stage 1, 2 to Stage 2, 3 to Stage 3, and 4 to Stage 4. Here, in this experiment, a semi-awake state of REM sleep has been assumed. It was given a weighting of 0.5 since the brain is in almost a fully awake state while the body is considered to be in a resting state [13].

Sleep efficiency was calculated from the ratio of sleep time to time in bed. The occurrence ratio of each sleep stage is defined as the ratio of data that was judged as, for example, Stage 3 during a given analysis period to the total data. The occurrence ratios of other sleep stages were computed in a similar manner.

2.7 Measurement of body motion during sleep

The actigraph (Ambulatory Monitoring, Inc. ("AMT"), U.S.A.) is a device for measuring behavior associated with body movement with a three-axis acceleration sensor during sleep and is widely used in sleep research for the determination of sleep and wakefulness. The sensor was

attached to the wrist of the non-dominant arm of the subject to evaluate quantitatively the movement of the upper limb and detect the body motion. The amount of body motion was estimated from corresponding values for each minute, counting the acceleration of more than 0.01G by using the actigraph.

The sleep-wake state was determined by the Cole formula using the count numbers [14]. Each sample was compared with sleep efficiency. Sleep efficiency is the percentage that sleep occupies in the entire percentage determined from the start of the experiment to 3 hours.

2.8 Mood survey

In order to evaluate sleeping comfort in each mattress sample, subjects were asked their moods by using POMS test before and after sleep. Using the POMS test system, 6 factors that concern human's mood and emotions (Tension – Anxiety (T-A), Depression – Dejection (D), Anger – Hostility (A-H), Vigor (V), Fatigue (F), and Confusion (C)) can be measured [15,16]. In order to analyze the data, the scores of each constituent item were totaled for each scale in order to calculate raw scores for every question except for dummy questions. The raw scores were then converted into standardized ones (T scores) to calculate the scores for each item. As an index for indicating overall mood conditions, total mood disturbance (TMD) score was calculated.

The TMD score was calculated where a score for vigor (positive factor) was deducted from the total scores of the five negative factors (those other than vigor). Based on differences in the moods of subjects before and after sleep, the effect of sleep in improving mood was verified and a comparison was made among samples. For each evaluation item, the representative value of the subjects was the average value.

3. RESULTS

3.1 Measurement of body subduction when lying on a mattress

Shown in Figure 3 are the sleeping posture curves observed when subjects were lying supine on each of the five types of mattresses with different degrees of elasticity. It was confirmed that the sleeping posture curves varied among different mattresses. The amount of sinking-in was large for portions with a low degree of elasticity, and displacement was greater for the area from the waist to the hip. The curve of the back could be classified into three categories: (1) Curve of ABAB, AAAA, BBBB. Buttocks are subducting more than the chest, but the difference is

Figure 3: Supine position lying postures for each sample

small. (2) Curve of BCBB. Sinking of the chest and hips are almost the same. (3) Curve of BBCB. There is no rounding of the chest. Curve from chest to buttocks is close to a straight line. We assumed that the differences in these curves may affect sleep.

3.2 Muscle blood flow

According to the results of subsection 3.1, we chose 3 mattresses, ABAB, BBCB, and BCBB as experimental samples.

The results of OxyHb, DeoxyHb in each sample are shown in Figure 4. OxyHb increased over time in each sample. The increase rate of OxyHB in BBCB is lower than in others. DeoxyHb did not change much in ABAB and BCBB, and decreased in BBCB compared with others.

The TotalHb results for each sample are shown in Figure 5. TotalHb increased over time in each sample. The increase rate of TotalHB in BBCB is lower than in others.

It was revealed that differences of the sample affect muscle metabolism when a person is lying on mattress. In particular, it was confirmed that in BBCB, oxygen supply quantity and muscle blood flow were decreased compared with other mattresses. From the above, it has been suggested that intramuscular metabolic reaction is different according to the hardness of the buttocks area. ANOVA and multiple comparisons using the Tukey method revealed significant differences in OxyHB between the respective samples, and significant differences in DeoxyHB and Total HB between samples ABAB and BBCB, and between samples BCBB and BBCB.

3.3 Estimation of sleep state

Using the data on the determined the sleep stages, sleep efficiency, the average sleep depth three hours after the experiment began was calculated. Table 4 shows the results of the sleep in each sample.

Figure 4: Results of OxyHB, DeoxyHB in each sample (N=3)

Figure 5: Results of TotalHB in each sample (N=3)

Sleep efficiency estimated by PSG showed no statistically significant difference between the samples. Average sleep depth, sleep efficiency (actigraph), were also deeper in the order of ABAB, AAAA, BBBB, BBCB and BCBB. ANOVA and multiple comparisons using the Tukey method did not show any statistically significant disparities among different samples.

Using the data on determined sleep stages, the occurrence ratios of each sleep stage within three hours after the experiment began were calculated. The occurrence ratios of each sleep stage for the samples are shown in Figure 6. The occurrence ratios of Stage W, Stage R, Stage 1, and Stage 2 did not vary much among samples, but those of deep sleep (Stage 3 and Stage 4 combined) were highest in ABAB and decreased steadily in the order AAAA, BBBB, BBCB and then BCBB. The occurrence ratios of each sleep stage did not show any statistically significant differences either.

In this experiment, no differences in the sleep states were found in the 5 type mattresses.

Table 4: The results of sleep for each sample (N = 5)

	Average sleep depth	Sleep efficiency (PSG)	Sleep efficiency (Actigraph)
ABAB	1.736 (SD:0.129)	97.78 (SD:1.66)	91.78 (SD:7.21)
AAAA	1.664 (SD:0.242)	94.61 (SD:5.10)	91.44 (SD:2.86)
BBBB	1.660 (SD:0.209)	96.67 (SD:2.18)	90.83 (SD:6.44)
BBCB	1.627 (SD:0.132)	97.33 (SD:1.76)	87.00 (SD:8.59)
BCBB	1.604 (SD:0.130)	97.28 (SD:1.90)	84.50 (SD:10.4)

Figure 6: Occurrence ratios of each sleep stage for each sample (N = 5)

3.4 Mood surveys

Figure 7 shows differences in the POMS test results of each sample before and after sleep. Scores for the factors of anger, vigor, depression and fatigue showed the tendency of positive mood change for mattresses other than BBCB. BBCB, rather than improving feelings, showed worsening results for each mood factor. In particular, it became clear that BBCB resulted in higher fatigue and anger after waking up compared with other mattresses. ANOVA and multiple comparisons using the Tukey method revealed significant differences in fatigue (F) and anger (A-H) factors between samples ABAB and BBCB, between samples AAAA and BBCB, between samples BBBB and BBCB, and between samples BCBB and BBCB, and significant differences in depression (D) factor between samples ABAB and BBCB, and between samples BCBB and BBCB.

Figure 8 shows the TMD scores for each sample before and after sleep. For samples ABAB and BBBB, TMD scores after sleep decreased compared to those before sleep with a significant difference using the Wilcoxon test. The improvement of moods after waking up in the ABAB and BBBB mattresses may positively correlate with the subjective feelings of sleep. On the other hand, TMD scores of BBCB increased before and after sleep with a significant difference, suggesting the deterioration of moods. This may result in negative subjective feeling of sleep.

Figure 7: Differences in T scores for each sample before and after sleep (N = 5)

Figure 8: TMD scores for each sample before and after sleep (N = 5)

4. DISCUSSION

We postulated that good comfort can be obtained in a sleeping posture corresponding to the mattresses with different elastic moduli for each body region. It was presumed that the status of mood was caused by the differences in hemodynamics according to the supine posture during sleep.

Based on the results of these experiments, we concluded that differences in hemodynamics are one of the factors in sleep comfort that changes the mood after getting up. Several studies have reported that increases in blood flow reduced pain [17, 18], or a bedding having moderate hardness, a so-called “not too soft and not too hard” mattress, reduces back-pain or makes it easy to roll over [8, 19, 20]. We regarded these reports to mean that hardness and blood flow affected comfort.

NIRS revealed that the blood flow of the biceps femoris is different for the three mattresses of ABAB, BBCB, and BCBB. Because AAAA and BBBB exceeded the hardness of BBCB in buttocks region, these mattresses were speculated to have tendencies toward similar hemodynamics to BCBB or ABAB. Mine et al. have reported that the metabolism during sleep falls about 10 % compared to being awake [21, 22]. Therefore, it is expected that intramuscular blood flow during sleep decreases compared to when a person is just lying down.

Regarding the results of POMS, improving trends of moods were observed in all mattresses with the exception of BBCB. In addition, the result of NIRS showed in the biceps femoris that muscle blood flow and oxygen supply quantity lying on BCBB and ABAB mattresses were larger than those on BBCB. Therefore, it may be possible that promotion of blood circulation at the buttock region leads to better mood during sleep. We revealed that mattress exceeding the modulus of elasticity of B (Spring constant: 0.01 kgf/mm) in

buttocks area improves promotion of blood circulation. This promotion of blood circulation can be considered as possibly due to the following: the muscle blood vessels were dilated by these blood flow increases. This dilation activates the metabolism, and relaxes vascular smooth muscles [23]. It is assumed that the dilation of blood vessels reduces pain, and fatigue is reduced by the promotion of metabolism.

On the other hand, BBCB worsened moods. This sample decreased muscle blood flow and oxygen supply quantity compared with the other mattresses according to NIRS. We considered that the mood deterioration was caused by poor blood circulation. We concluded that the low modulus of elasticity (Spring constant: 0.0072 kgf/mm) of the buttocks area worsened blood circulation. Poor blood circulation can be considered as possibly due to the following: reduction of intramuscular blood flow reduces supply of glycogen and oxygen, causing muscle contraction by anaerobic metabolism that utilizes the glycogen. Acidosis occurs with lactic acid and proton (H⁺) as an intermediate metabolite of this metabolism. Acidosis is one of the major factors of muscle fatigue [24]. Acidosis induced muscle fatigue due to the reduced metabolism and a lot of lactic acid accumulated in the muscles during sleep. In experiments that examined the subjective evaluation and EMG measurement of the waist, Oka reported that subjective fatigue and muscle fatigue are related [25]. Therefore, it is suggested that muscle fatigue due to poor blood circulation may have worsened items such as TMD score and fatigue in the POMS test.

From the findings described above, we mentioned the possibility that variations of intramuscular metabolic reactions during sleep affects mood. For mattresses with different elastic moduli for each body region, we showed that differences in hemodynamics at the buttock region are one of the factors of sleep comfort that change the mood after getting up. Therefore, we concluded that measurements of blood flow of the biceps femoris are likely to be useful indicators when choosing a mattress or designing mattresses.

We hope that this information will be useful when choosing a mattress or design and mattress. In this research, however, the subjects of the experiments were all male university students with a standard physique. We assume that variances in the physique, gender, and age of subjects may result in different effects from mattresses. For example, obese subjects would be expected to experience greater sinking into the mattress than subjects with a standard physique, and the results of experiments would thus differ from those conducted on subjects with a standard physique.

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