World Academy of Science, Engineering and Technology
International Journal of Biomedical and Biological Engineering
Vol:10, No:7, 2016

Development of Sleep Quality Index Using Heart Rate

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***Abstract*—**Adequate sleep affects various parts of one's overall physical and mental life. As one of the methods in determining the appropriate amount of sleep, this research presents a heart rate based sleep quality index. In order to evaluate sleep quality using the heart rate, sleep data from 280 subjects taken over one month are used. Their sleep data are categorized by a three-part heart rate range. After categorizing, some features are extracted, and the statistical significances are verified for these features. The results show that some features of this sleep quality index model have statistical significance. Thus, this heart rate based sleep quality index may be a useful discriminator of sleep.

***Keywords*—**Sleep, sleep quality, heart rate, statistical analysis.

I. Introduction

SLEEP affects various parts of our lives and plays a vital role in good health. Getting good sleep in quantity and quality helps our brains to work properly. As a method of evaluating the quality of sleep, the Pittsburgh Sleep Quality Index (PSQI) [1], which is a self-rated questionnaire administered over a 1-month time interval, has gained widespread acceptance as a useful tool to measure the sleep quality in different patient groups. After the development of the PSQI, many similar studies have been performed, including research related to the evaluation of the PSQI [2], [3] and research applying the PSQI [4], [5]. These studies, as well as the PSQI itself, are mostly based on subjective questionnaires. Therefore, in this research, some objective biological signals that can be obtained from a wearable device are used to evaluate the quality of sleep.

With the development of a number of wearable devices, it has become possible to acquire personal data without the help of complex medical equipment. Among these data, the heart rate is the core of this research. The heart rate can be affected by several peripheral elements such as age, air temperature, body position, emotion, body size, and medication use. But, in general, a small variation of heart rate is considered as normal unless the person is engaged in physical activity. Heart rate analysis can be applied during sleep. If the heart rate increases when there are no movements during sleep, it can be estimated that there is some abnormality in the internal body that is affecting the sleep quality. Therefore, in this research, the sleep quality index is evaluated by evaluating the heart rate during sleep.

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II. Materials and Methods

A. Device for Data Acquisition

The device that is used for this research is a Fitbit Charge HR. The Fitbit Charge HR is a wristband-type wearable device that uses a MEMS 3-axis accelerometer, an altimeter, and an optical heart rate tracker to measure the motion patterns to track the following all-day stats: steps, distance, calories, floors, heart rate, and sleep. The Fitbit provides a Web API for accessing data from the Fitbit device and entering logs. Through this procedure, heart rate time series and sleep data can be acquired. Heart rate data and sleep data are provided in the form of beats per minute (bpm) and sleep mode values for every minute, respectively.

B. Heart Rate Based Sleep Quality Index Model

Fig. 1 shows a schematic of the heart rate based sleep quality index models. From the Fitbit cloud server, the heart rate and sleep data are acquired. In order to determine the sleep quality index, first of all, the non-sleep state data must be filtered out. The Fitbit Charge HR marks sleep data in three types of mode: asleep as "1", awake as "2", and really awake as "3". If there are no sleep mode values for a specific time, those data were excluded for the following steps. After excluding non-sleep state data, the filtered data are classified by the criteria of heart rate in bpm.

The criteria are evaluated based on the maximum heart rate. In this research, for ease-of-implementation, the following equation, which is the most widely cited formula for maximum heart rate, is used:

$$HR_{max} = 220 - age \tag{1}$$

If the heart rate is lower than 50% of the maximum heart rate, it is considered a non-exercising state [6]. Also, when people sleep, there is a certain drop in the heart rate of about 8% [7]. With this information, the normal range of heart rate during sleep can be evaluated. The upper bound of the normal range is 42% of the maximum heart rate, which is 8% lower than the upper limit of the non-exercise state. The lower bound is set at 27% of the maximum heart rate.

With these criteria, data are divided into the following three ranges: low heart rate range, normal heart rate range, and high heart rate range. After dividing the ranges, the sleep ratio, which is the ratio of the normal to total heart range sleep, is calculated:

$$Sleep\ Ratio = \frac{Minutes\ of\ Normal\ Heart\ Rate\ Range\ Sleep}{Total\ Sleep\ Minutes} \tag{2}$$

Finally, the sleep quality index is defined by using the sleep ratio value.

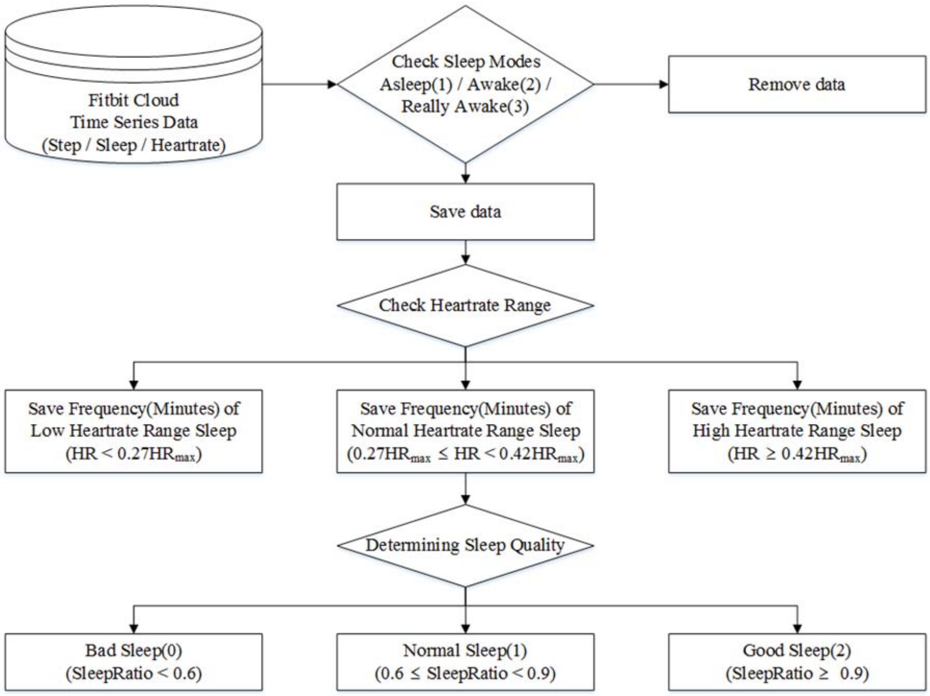

Fig. 1 Scheme of heart rate based sleep quality index model

C. Statistical Analysis

After obtaining Institutional Review Board (IRB) approval (no. DGIST-160303-HR-012-01) from DGIST, this research collected data from empirical subjects for one month from March 7th to April 6th. The subjects are 280 general company employees who do not have any special diseases. There were encouraged to wear the Fitbit Charge HR every day but, because of certain practical reasons such as charging the device or device failure, the number of sleep data collected during this period was 2925; the distribution of the demographical characteristics is shown below:

TABLE I
DISTRIBUTION IN TERMS OF AGE GROUP AND SEX

		Sex		Total
		Male	Female	
Age Groups	20's	613	212	825
	30's	1214	27	1241
	40's	708	17	725
	50's	134	0	134
Total		2669	256	2925

As shown in Table I, there is a serious imbalance in sex. Therefore, in this research, in order to prevent bias, the sleep data only from males are used. With the data divided based on heart rate range, it is possible to extract various features: average heart rate value, minutes of sleep, and sleep mode count value for each heart rate range sleep. In this research, the extracted features are statistically analyzed with age groups and Body Mass Index (BMI) level. As ages and BMI levels are divided into more than three groups, one-way analysis of variance (one-way ANOVA) [8], a technique used to compare means of three or more samples, is performed for these features.

III. RESULTS

In this section, the results of the one-way ANOVA for the extracted features with age and BMI level are presented. In this research, BMI is categorized into four levels [9]: underweight, normal, overweight, and obese.

A. Average Heart Rate during Sleep in Terms of Age

TABLE II
RESULTS OF THE TEST OF HOMOGENEITY OF VARIANCES

	Levene Statistic	*p*-value
Average Heart Rate during Low Heart Rate Sleep	19.302	0.000
Average Heart Rate during Normal Heart Rate Sleep	6.909	0.000
Average Heart Rate during High Heart Rate Sleep	5.241	0.001

TABLE III
DESCRIPTION OF AVERAGE HEART RATE DURING EACH HEART RATE LEVEL SLEEP

Heart Rate Range	Age Group	Mean	Std. Deviation
Low Heart Rate Sleep	20's	49.25	2.45
	30's	48.07	1.46
	40's	46.19	1.03
	50's		
Normal Heart Rate Sleep	20's	62.93	5.87
	30's	62.15	5362
	40's	62.38	5.86
	50's	61.71	4.32
High Heart Rate Sleep	20's	87.82	10.53
	30's	83.16	7.30
	40's	80.27	6.93
	50's	75.05	3.40

Because the p-value of each heart rate range in the test of homogeneity of variances is lower than 0.05, the null hypothesis of equal variances is rejected. Therefore, in this research, more generalized tests that are free from homoscedasticity assumptions are used.

TABLE IV
RESULTS OF POST HOT TESTS

	Age Group (i)	Age Group (j)	Mean Difference (i-j)	Std. Error	*p*-value
Average Heart Rate of Normal Heart Rate Sleep	20's	30's	0.78	0.29	0.040
		40's	0.56	0.33	0.426
		50's	1.22	0.45	0.044
	30's	20's	-0.78	0.29	0.040
		40's	-0.23	0.28	0.960
		50's	0.44	0.42	0.877
	40's	20's	-0.56	0.33	0.426
		30's	0.23	0.28	0.960
		50's	0.66	0.44	0.587
	50's	20's	-1.22	0.45	0.044
		30's	-0.44	0.42	0.877
		40's	-0.66	0.44	0.587
Average Heart Rate of High Heart Rate Sleep	20's	30's	4.65	0.57	0.000
		40's	7.54	0.59	0.000
		50's	12.76	0.60	0.000
	30's	20's	-4.65	0.57	0.000
		40's	2.89	0.38	0.000
		50's	8.11	0.39	0.000
	40's	20's	-7.54	0.59	0.000
		30's	-2.89	0.38	0.000
		50's	5.22	0.42	0.000
	50's	20's	-12.76	0.60	0.000
		30's	-8.11	0.39	0.000
		40's	-5.22	0.42	0.000

It can be seen in the results that for normal heart rate sleep, there are no statistically significant differences for most age groups, except for the 20's and 30's, and the 20's and 50's. However, in the high heart rate sleep, the results show that there are statistically significant differences for all age groups.

B. Minutes of Each Heart Rate Range during Sleep in Terms of Age

TABLE V
RESULTS OF THE TEST OF HOMOGENEITY OF VARIANCES

	Levene Statistic	*p*-value
Minutes of Low Heart Rate Sleep	47.06	0.000
Minutes of Normal Heart Rate Sleep	4.77	0.003
Minutes of High Heart Rate Sleep	78.74	0.000

TABLE VI
DESCRIPTION OF SLEEP MINUTES DURING EACH HEART RATE LEVEL SLEEP

Heart Rate Range	Age Group	Mean	Std. Deviation
Low Heart Rate Sleep	20's	32.79	80.41
	30's	19.65	62.36
	40's	12.54	51.07
	50's	0.00	0.00
Normal Heart Rate Sleep	20's	19.80	63.36
	30's	331.49	152.74
	40's	342.31	146.76
	50's	312.36	161.30
High Heart Rate Sleep	20's	307.31	160.05
	30's	330.12	153.28
	40's	31.97	73.92
	50's	32.64	79.88

Because the *p*-value of each heart rate range in the test of homogeneity of variances is lower than 0.05, the post hoc test is performed.

TABLE VII
RESULTS OF POST HOT TESTS

	Age Group (i)	Age Group (j)	Mean Difference (i-j)	Std. Error	*p*-value
Minutes of Low Heart Rate Sleep	20's	30's	13.15	3.71	0.002
		40's	20.25	3.77	0.000
		50's	32.79	3.25	0.000
	30's	20's	-13.15	3.71	0.002
		40's	7.11	2.62	0.040
		50's	19.65	1.79	0.000
	40's	20's	-20.25	3.77	0.000
		30's	-7.11	2.62	0.040
		50's	12.54	1.92	0.000
	50's	20's	-32.79	3.25	0.000
		30's	-19.65	1.79	0.000
		40's	-12.54	1.92	0.000
Minutes of Normal Heart Rate Sleep	20's	30's	-10.82	7.47	0.617
		40's	19.12	8.65	0.153
		50's	24.17	15.14	0.510
	30's	20's	10.82	7.47	0.617
		40's	29.94	7.38	0.000
		50's	34.99	14.45	0.096
	40's	20's	-19.12	8.65	0.153
		30's	-29.94	7.38	0.000
		50's	5.05	15.10	1.000
	50's	20's	-24.17	15.14	0.510
		30's	-34.99	14.45	0.096
		40's	-5.05	15.10	1.000
Minutes of High Heart Rate Sleep	20's	30's	-0.67	3.76	1.000
		40's	-36.82	5.33	0.000
		50's	-77.72	12.81	0.000
	30's	20's	0.67	3.76	1.000
		40's	-36.15	4.97	0.000
		50's	-77.05	12.66	0.000
	40's	20's	36.82	5.33	0.000
		30's	36.15	4.97	0.000
		50's	-40.90	13.21	0.014
	50's	20's	77.72	12.81	0.000
		30's	77.05	12.66	0.000
		40's	40.90	13.21	0.014

These results show that there are some statistically significant differences in most age groups for low heart rate sleep and high heart rate sleep. Therefore, these features can be used to analyze the quality of the sleep.

C. Average Heart Rate during Sleep in Terms of BMI

TABLE VIII
RESULTS OF THE TEST OF HOMOGENEITY OF VARIANCES

	Levene Statistic	*p*-value
Average Heart Rate during Low Heart Rate Sleep	5.72	0.001
Average Heart Rate during Normal Heart Rate Sleep	6.90	0.000
Average Heart Rate during High Heart Rate Sleep	4.25	0.005

TABLE IX
DESCRIPTION OF AVERAGE HEART RATE DURING EACH HEART RATE LEVEL SLEEP

Heart Rate Range	BMI Level	Mean	Std. Deviation
Low Heart Rate Sleep	Underweight	48.82	0.27
	Normal	47.88	2.04
	Overweight	48.83	2.08
	Obese	48.82	2.44
Normal Heart Rate Sleep	Underweight	61.18	4.72
	Normal	61.41	5.87
	Overweight	63.11	5.44
	Obese	64.42	5.03
High Heart Rate Sleep	Underweight	82.78	5.06
	Normal	83.42	10.29
	Overweight	82.25	6.90
	Obese	82.52	6.14

Because the *p*-value of each heart rate range in the test of homogeneity of variances is lower than 0.05, the post hoc test is performed.

TABLE X
RESULTS OF POST HOT TESTS

	BMI Level (i)	BMI Level (j)	Mean Difference (i-j)	Std. Error	*p*-value
Average Heart Rate of Low Heart Rate Sleep	Underweight	Normal	0.94	0.14	0.000
		Overweight	-0.01	0.18	1.000
		Obese	0.00	0.49	1.000
	Normal	Underweight	-0.94	0.14	0.000
		Overweight	-0.95	0.18	0.000
		Obese	-0.94	0.49	0.329
	Overweight	Underweight	0.01	0.18	1.000
		Normal	0.95	0.18	0.000
		Obese	0.01	0.50	1.000
	Obese	Underweight	0.00	0.49	1.000
		Normal	0.94	0.49	0.329
		Overweight	-0.01	0.50	1.000
Average Heart Rate of Normal Heart Rate Sleep	Underweight	Normal	-0.24	0.88	1.000
		Overweight	-1.93	0.88	0.193
		Obese	-3.24	0.94	0.008
	Normal	Underweight	0.24	0.88	1.000
		Overweight	-1.70	0.23	0.000
		Obese	-3.01	0.41	0.000
	Overweight	Underweight	1.93	0.88	0.193
		Normal	1.70	0.23	0.000
		Obese	-1.31	0.41	0.009
	Obese	Underweight	3.24	0.94	0.008
		Normal	3.01	0.41	0.000
		Overweight	1.31	0.41	0.009
Average Heart Rate of High Heart Rate Sleep	Underweight	Normal	-0.64	1.05	0.991
		Overweight	0.53	1.02	0.996
		Obese	0.26	1.10	1.000
	Normal	Underweight	0.64	1.05	0.991
		Overweight	1.17	0.42	0.029
		Obese	0.90	0.59	0.569
	Overweight	Underweight	-0.53	1.02	0.996
		Normal	-1.17	0.42	0.029
		Obese	-0.28	0.53	0.996
	Obese	Underweight	-0.26	1.10	1.000
		Normal	-0.90	0.59	0.569
		Overweight	0.28	0.53	0.996

From Table X, the most noticeable fact is that the average heart rate of normal heart rate sleep is significantly different between the obese and the non-obese.

D. Minutes of Each Heart Rate Range during Sleep in Terms of BMI

TABLE XI
RESULTS OF THE TEST OF HOMOGENEITY OF VARIANCES

	Levene Statistic	*p*-value
Minutes of Low Heart Rate Sleep	86.13	0.000
Minutes of Normal Heart Rate Sleep	3.94	0.008
Minutes of High Heart Rate Sleep	7.13	0.000

TABLE XII
DESCRIPTION OF SLEEP MINUTES DURING EACH HEART RATE LEVEL SLEEP

Heart Rate Range	Age Group	Mean	Std. Deviation
Low Heart Rate Sleep	20's	2.23	5.46
	30's	30.99	81.40
	40's	10.39	39.11
	50's	6.88	36.48
Normal Heart Rate Sleep	20's	396.43	139.78
	30's	315.28	158.09
	40's	341.68	147.39
	50's	344.72	150.51
High Heart Rate Sleep	20's	17.47	26.37
	30's	42.91	99.70
	40's	45.37	92.12
	50's	76.28	104.86

Because the *p*-value of each heart rate range in the test of homogeneity of variances is lower than 0.05, the post hoc test is performed.

TABLE XIII
RESULTS OF POST HOT TESTS

	Age Group (i)	Age Group (j)	Mean Difference (i-j)	Std. Error	*p*-value
Minutes of Low Heart Rate Sleep	20's	30's	-28.75	2.50	0.000
		40's	-8.16	1.51	0.000
		50's	-4.64	2.87	0.493
	30's	20's	28.75	2.50	0.000
		40's	20.59	2.56	0.000
		50's	24.11	3.53	0.000
	40's	20's	8.16	1.51	0.000
		30's	-20.59	2.56	0.000
		50's	3.52	2.92	0.791
	50's	20's	4.64	2.87	0.493
		30's	-24.11	3.53	0.000
		40's	-3.52	2.92	0.791
Minutes of Normal Heart Rate Sleep	20's	30's	81.16	25.91	0.022
		40's	54.76	25.88	0.230
		50's	51.71	27.83	0.355
	30's	20's	-81.16	25.91	0.022
		40's	-26.40	6.17	0.000
		50's	-29.45	11.96	0.084
	40's	20's	-54.76	25.88	0.230
		30's	26.40	6.17	0.000
		50's	-3.05	11.89	1.000
	50's	20's	-51.71	27.83	0.355
		30's	29.45	11.96	0.084
		40's	3.05	11.89	1.000
Minutes of High Heart Rate Sleep	20's	30's	-25.44	5.57	0.000
		40's	-27.90	5.51	0.000
		50's	-58.81	9.11	0.000
	30's	20's	25.44	5.57	0.000
		40's	-2.46	3.88	0.989
		50's	-33.37	8.22	0.000
	40's	20's	27.90	5.51	0.000
		30's	2.46	3.88	0.989
		50's	-30.91	8.18	0.001
	50's	20's	58.81	9.11	0.000
		30's	33.37	8.22	0.000
		40's	30.91	8.18	0.001

Table XIII shows that the minutes of low heart rate sleep are significantly different between normal and other BMI levels. In addition, there are differences between underweight and other BMI levels in the case of minutes of high heart rate sleep.

IV. Conclusion

This research suggests a heart rate based sleep quality index model. After classifying sleep by considering the heart rate, statistical analysis was performed on the extracted features such as average heart rate and minutes of each heart rate sleep. Through the statistical analysis, several factors were found to have statistical significance: age and BMI level. These features are useful for not only this research but also for the future works that will evaluate the sleep quality index.

Unfortunately, there are some imbalances in the data because of practical reasons. In order to overcome some of the imbalances in the data, if it is difficult to resolve these problem directly, a propensity score analysis may also be considered as a solution in the future work. Finally, this work could be adapted to sleep apnea subjects.

Acknowledgment

This work was supported by the R&D Program of the Ministry of Trade, Industry and Energy of Korea (Program of Advanced Technology Development for Future Industry, 10044323).

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