

# Unique Characteristics of Heart Rate Variability Obtained from Pulse Wave Signals during Work

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**Abstract**—To examine the basic characteristics of Pulse Rate Variability (PRV) during work, pulse wave signals during work hours were recorded by wristband-type wearable sensors in 8 office workers for 1-3 months together with the signals of physical activity, skin temperature, and the amount of conversation and with subjective emotions. A total of 1,544 hours of data were obtained. Pulse rate increased during physical activity and decreased during dozing. Although High Frequency (HF) component of Heart Rate Variability (HRV) is known as an index of parasympathetic function and increases during rest and sleep, HF amplitude of PRV during work increased with mild physical movement detected at the wrist and decreased during dozing. Factor analysis revealed that there were two factors, reflecting slow and fast variations, respectively, among the indices of PRV indices (the amplitude of very low, low, and HF components and their standard deviations). While factor 1 score decreased during walking and increased with mild physical movement, it also increased when subjects reported angry emotion. While factor 2 score also increased with mild physical movement, it also increased with happiness and relax compared with sad and angry emotions. This study suggests on one hand that HF amplitude of PRV at least that obtained through wristband-type sensors during work cannot be used as the indices of parasympathetic function and resting. On the other hand, PRV may provide unique information from that of HRV. The HF amplitude of PRV may reflect positive feeling for work, while an increase in slow variation of PRV may reflect their conflict and dissatisfaction during work.

**Index Terms**—wearable sensor, biosignal, pulse wave, pulse rate variability, heart rate variability, work, job stress, physical activity, emotion

## I. INTRODUCTION

Analysis of Heart Rate Variability (HRV) has been used widely for assessing autonomic functions in various fields [1]. For this purpose, the specific frequency components of HRV are used as autonomic indices [2]. High Frequency (HF) component is defined as the fluctuation between 0.15 and 0.40 Hz [3]. This component is the quantitative reflection of respiratory

variation of heart rate (respiratory sinus arrhythmia) [4]. HF component is mediated purely by the vagus (parasympathetic nerves innervating the heart) and its power (or amplitude) reflects cardiac vagal function [5]. Respiratory sinus arrhythmia is thought as a physiological function to save energy of circulation and respiration by optimizing the timing of heartbeats and respiratory cycle [4]. HF component is also thought to reflect the resting function of cardiorespiratory systems [6]. The Low Frequency (LF) component of HRV is defined as the fluctuation between 0.04 and 0.15 Hz [3]. This component is mediated by both cardiac vagus and sympathetic nerves and the LF-to-HF ratio in power (LF/HF) is widely used as the index of sympathetic predominance [7], [8], although the interpretations of LF component and LF/HF as the autonomic function is still subject to the discussion [9]-[12]. The very Low-Frequency Component (VLF) is defined as the fluctuation between 0.0033 and 0.04 Hz. This component is thought to reflect nonlinear fluctuations including both the responses to various intrinsic and extrinsic stimuli and spontaneous fractal variation [13]-[15]. Finally, Standard Deviation (SD) of the beat-to-beat interval is also used as an estimate of the overall magnitude of HRV.

Analysis of HRV has been increasingly used also in the workplace for the purpose of improving the work environment and productivity as well as stress and health management of workers [16], [17]. Although HRV is usually assessed from R-R interval of electrocardiogram (ECG), the long-term and frequent attachment of ECG electrodes is burdensome to workers. Compared with ECG, pulse wave that can be measured with a single sensor by just attaching it to the skin seems attractive as the signal for the analysis of variability in the workplace. As the result, along with widespread use of wearable pulse wave sensors, many companies are considering the introduction of this technique to the workplace.

However, physiological properties of Pulse Rate Variability (PRV) are not the same as those of HRV. First, HRV is measured from the intervals between consecutive R waves that are the sharp peaks of the electrophysiological signal. In contrast, PRV is measured from pulse wave that is tissue blood flow/volume change

forming slow peaks. Second, the shape of the peaks changes with stroke volume, blood pressure, pulse wave velocity and the pressure reflection from peripheral vasculatures, which are affected by body posture, respiration, and emotions [18]. In fact, the correlation of HF amplitude between HRV and PRV even at rest is modest, even when the correlation between heart rate and Pulse Rate (PR) is high [19]. Finally, the measurement of pulse wave during work hours may be affected by body movements that may distort the pulse waveform through the inertia force in arterial and tissue blood and the contact failure of the sensor. These suggest that physiological features of HRV built up by previous studies may not apply to PRV particularly that is obtained in the workplace by wearable sensors.

In this study, we, therefore, examined the basic characteristics of PRV during work. We recorded pulse wave signals during work hours by wristband-type wearable sensors in office workers together with the signals of physical activity, skin temperature, and the amount of conversation and with subjective emotions.

## II. METHODS

### A. Subjects and Protocol

Subjects were 8 healthy individuals (2 female). They participated in this study for 1-3 months, during which they attached a wristband-type biometric sensor (Silme W20, TDK Co., Japan) between 0830h and 2130h every day except holidays. This device was about  $20.5 \times 65 \times 12.5$  mm (thickest part) and weighted about 29.5 with built-in sensors for acceleration, pulse wave, environmental ultraviolet light, skin temperature, and sound, by which it detect continuously body movement at their wrist (level and kind), beat-to-beat Pulse Intervals (PI), step count, metabolic equivalents (METs), wrist skin temperature, and the periods of body movement, conversation, and sleep (dozing). During the experiment, subjects were instructed to record the emotional labels (happy, angry, relaxed, and sad) every 30 min when feeling strong emotions.

### B. Data Analysis

PRV was analyzed by the method of Complex Demodulation (CDM) [20], [21]. CDM is a time domain method for time series analysis which provides the instantaneous amplitude and frequency of fluctuation in a specified frequency band as continuous functions of time. In this study, amplitudes and frequencies of VLF, LF, and HF components of PRV were demodulated. For CDM, PI time series were processed for filtering “abnormal” data that were assumed as those caused by ectopic beats or noises. Filtered data were interpolated by a linear step function using only “normal” PI, resampled at 2 Hz, and submitted to CDM procedure.

Continuous functions of amplitude and frequency for each frequency band were averaged over every 5 min.

Mean and standard deviation of PI (SDPI), LF/HF of their power (squared ratio of the heir amplitudes), and SD of VLF, LF, and HF amplitudes (VLFsd, LFsd, and HFsd) were also calculated for the same time frame. Synchronizing with the same time frame, METs and skin temperature were averaged and step count, moving, conversation, and sleeping times were summed up for 5 min.

### C. Subjects and Protocol

Statistical Analysis System (SAS Institute, Cary, NC) was used. PRV indices in the individual subject were standardized with  $z$ -transformation ( $[x - \text{mean}]/\text{SD}$ ) to adjust for the effect of individual differences. The associations between PRV indices and other biometric data were analyzed with Pearson’s correlation coefficient. The differences in measures with the kind of activities, conversation, and sleep were evaluated by ANOVA with SAS Mixed model procedure.

Factor analysis was performed to delineate the features that were measured by PRV indices during work. In SAS FACTOR procedure, the principal component analysis was used for examining eigenvalues and factors with eigenvalue  $\geq 1$  were extracted. Squared multiple correlations were used as coefficients for communality estimates and were inserted in the diagonal elements. Principal-axes factor analysis was iterated until no changes in the third decimal place of communality estimates were observed. The orthogonal factors were rotated with the varimax criterion.

The associations between factor scores and activity, conversation, and sleep were analyzed by SAS General Linear model procedure. The type I error level was set at  $P < 0.05$ .

TABLE I. MEAN AND SD OF BIOMETRIC DATA

Variable	Analyzable data, h	Mean	SD
PR, bpm	1544	74	10
SDPI, ms	1544	46	22
VLF, ms	1544	48	24
LF, ms	1544	28	9
HF, ms	1544	23	8
HF frequency, Hz	1340	0.28	0.01
VLFsd, ms	1514	23	16
LFsd, ms	1514	14	6
HFsd, ms	1508	14	5
Step, count /min	1544	8	45
METs	1544	0.40	0.48
Moving time, min	1544	4	1
Skin temperature, °C	1544	31.6	6.4
Conversation time, min	1486	1	2

TABLE II. CORRELATION OF PULSE RATE VARIABILITY (PRV) MEASURES WITH PHYSICAL ACTIVITY, SKIN TEMPERATURE, AND CONVERSATION TIME

	Correlation coefficient Significance				
	Step count	METs	Moving time	Skin temperature	Conversation time
PR	0.31	0.21	0.08	-0.04	0.06
	<.0001	<.0001	<.0001	<.0001	<.0001
SDPI	0.11	0.15	0.17	0.01	-0.02
	<.0001	<.0001	<.0001	0.3	0.01
VLF	0.06	0.13	0.15	0.03	-0.01
	<.0001	<.0001	<.0001	<.0001	0.4
LF	-0.08	0.05	0.23	0.01	0.01
	<.0001	<.0001	<.0001	0.1	0.04
HF	-0.01	0.08	0.31	-0.06	-0.07
	0.4	<.0001	<.0001	<.0001	<.0001
HF frequency	-0.06	-0.07	-0.21	0.09	0.08
	<.0001	<.0001	<.0001	<.0001	<.0001
VLFsd	0.02	-0.01	-0.02	-0.10	-0.02
	0.04	0.1	0.01	<.0001	0.003
LFsd	0.04	0.08	0.12	0.03	0.02
	<.0001	<.0001	<.0001	<.0001	0.03
HFsd	-0.03	0.04	0.15	0.01	0.02
	0.0003	<.0001	<.0001	0.08	0.001

All data were measured every min and averaged over 5 min. Before calculating correlation coefficient, PR and PRV indices were standardized by the mean and SD of individual subjects.

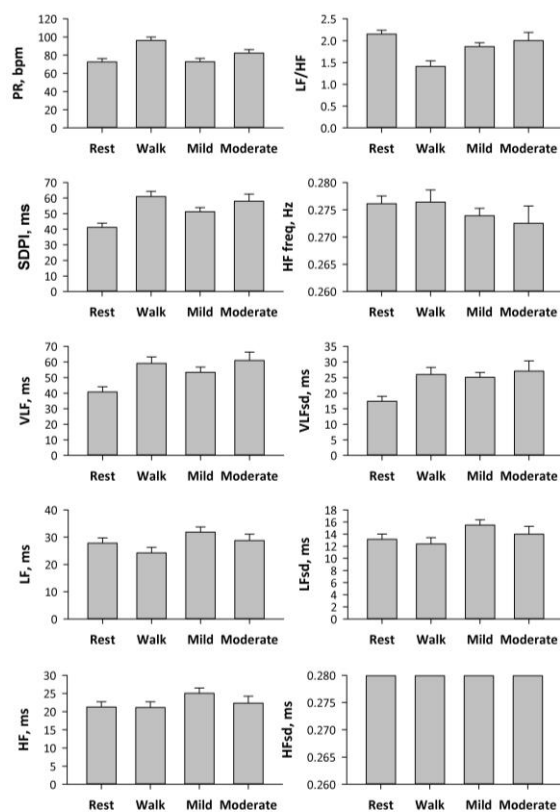


Figure 1. Changes in PR and PRV indices with activity state estimated from actigraphic data. Data are least-square means and error bars denote SE of the means.  $P < 0.0001$  for the effects of activity type on all parameters.

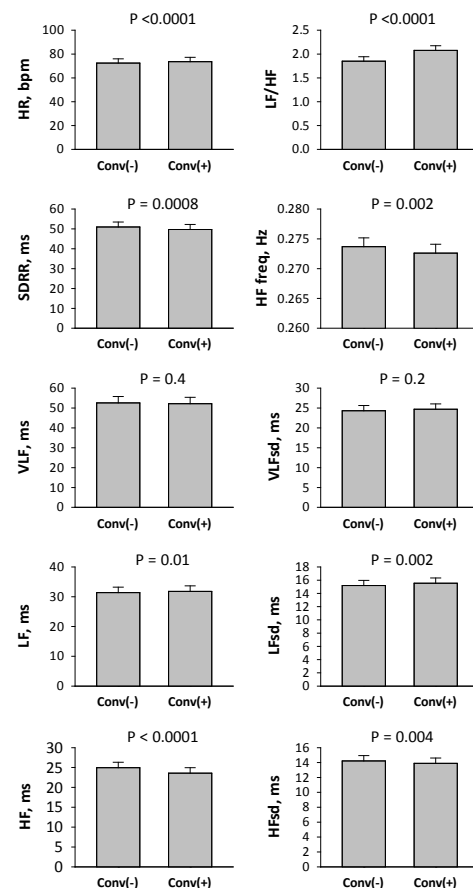


Figure 2. Effects of conversation on PR and PRV indices. Data are least-square means and error bars denote SE of the means.

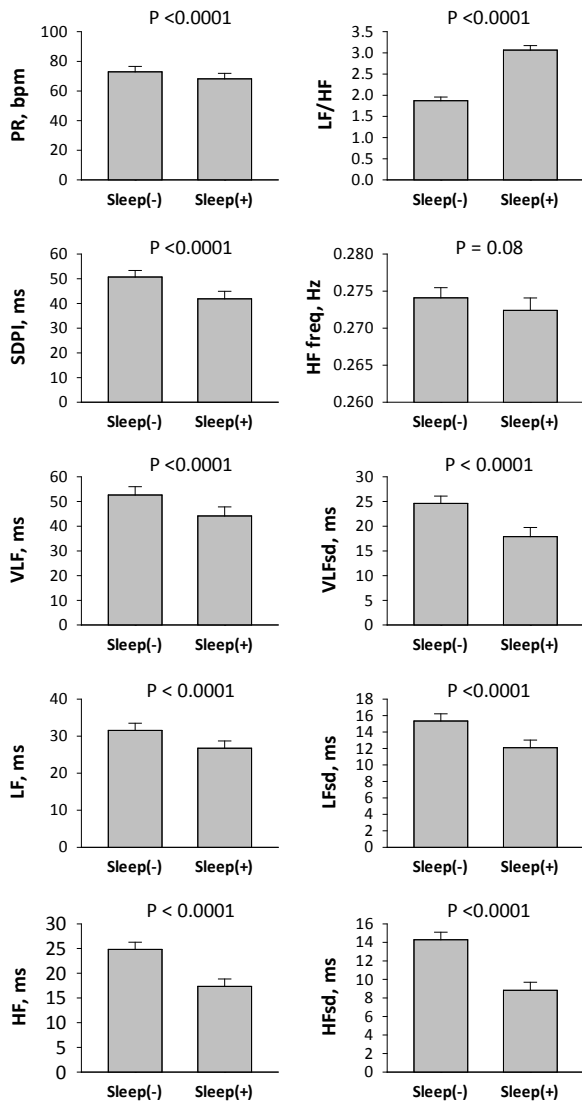


Figure 3. Effects of sleep on PR and PRV indices. Data are least-square means and error bars denote SE of the means.

TABLE III. ROTATED FACTOR PATTERNS

Variable	Factor 1	Factor 2
	Slow variation	Fast variation
PR	-0.38	-0.05
SDPI	0.74	0.23
VLF	<b>0.83</b>	0.10
LF	<b>0.80</b>	0.16
HF	0.43	<b>0.80</b>
LF/HF	0.28	<b>-0.82</b>
HF frequency	-0.27	0.10
VLFsd	<b>0.81</b>	0.13
LFsd	0.77	0.18
HFsd	0.51	0.67

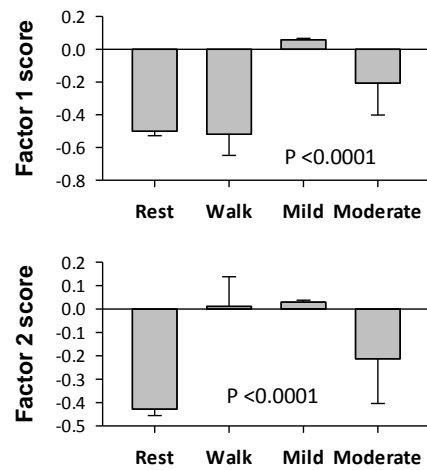


Figure 4. Changes in factors constituting PRV with activity state. Data are least-square means and error bars denote SE of the means.

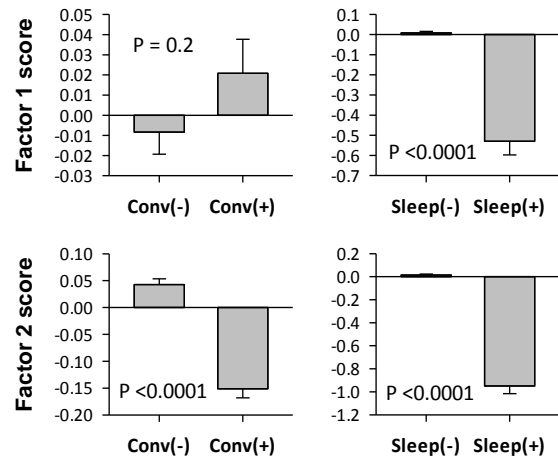


Figure 5. Changes in factors constituting PRV with conversation and sleep. Data are least-square means and error bars denote SE of the means.

### III. RESULTS

A total of 1544 h of data were obtained from 8 subjects. The PRV indices and biometric information and the correlations between them are presented in Table I and Table II. As expected, PR was correlated with step count and METs. LF and HF amplitude correlated positively with moving time.

Fig. 1 presents the changes in PR and PRV indices with activity state estimated from actigraphic data. PR increased during walking and moderate body movement. While LF amplitude of PRV decreased during walking and HF amplitude decreased during conversation (Fig. 2), both of them increased with mild body movement (Fig. 1) and decreased during sleeping (Fig. 3).

TABLE IV. CORRELATION OF FACTORS CONSTITUTING PRV WITH PHYSICAL ACTIVITY, SKIN TEMPERATURE, AND CONVERSATION TIME

	Correlation coefficient Significance				
	Step count	METs	Moving time	Skin temperature	Conversation time
Factor 1 score	-0.008	0.094	0.193	0.015	0.011
	0.2	<.0001	<.0001	0.06	0.1
Factor 2 score	0.031	0.092	0.301	-0.083	-0.079
	<.0001	<.0001	<.0001	<.0001	<.0001

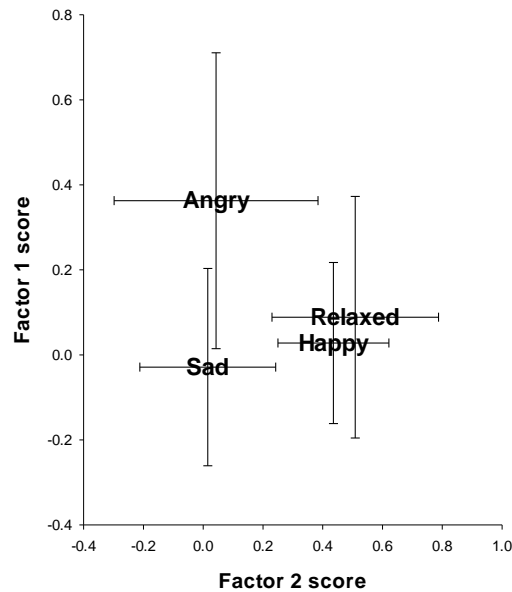


Figure 6. Relationships between factor scores and subjective emotions.

Factor analysis to extract information underlying PRV indices during work revealed that there two eigenvalues >1.0 that explained 83% of the variance of PRV indices. Table III shows the rotated factor pattern of these factors. Factor 1 was contributed strongly by VLF amplitude, VLFsd, and LF amplitude and thus, interpreted as reflecting the slow variation of PRV. Factor 2 was contributed by HF amplitude and negatively by LF/HF and thus, interpreted as reflecting the fast variability of PRV.

Table IV shows the correlation of factors constituting PRV with physical activity, skin temperature, and moving and conversation time. Factor 2 score correlated closely with moving time. Factor 1 score decreased during walking and increased with mild body movement compared with during rest (Fig. 4). It decreased during sleep (Fig. 5). Factor 2 score increased during walking and mild body movement (Fig. 4) and decreased during conversation and sleep (Fig. 5).

Fig. 6 shows the results of the analysis of the relationships between factors and subjective emotions. Angry was associated with an increase in factor 1 score, while the other emotions caused only small changes in factor 1 score. In contrast, happiness and relaxed feeling were associated with increases in factor 2 score, while angry and sad were accompanied by no significant change in factor 2.

#### IV. DISCUSSION

To examine the basic characteristics of PRV during work, PRV was analyzed from pulse wave signals in 8

office workers during long-term monitoring by the wristband-type wearable sensor. We observed the unique characteristics of PRV that are not known for HRV. The results of this study suggest that PRV during work has different physiological features from those of HRV. The knowledge accumulated for HRV such as its relationships with autonomic functions may not be able to apply to the interpretation of PRV during work at least that obtained by wristband type pulse wave sensors.

In contrast to HF component of HRV that is known as an index of cardiac parasympathetic function [1], [2], [5] or cardiorespiratory resting state [6], HF component of PRV obtained in this study increased during walking and mild body movement that is thought as the states of decreased parasympathetic function. This indicates that the HF amplitude of PRV during work is not an index of parasympathetic function.

This increase in HF amplitude seems to result from the effect of body movement particularly at the place of sensor mounting site, i.e., the wrist. The movement may cause high-frequency artifacts in pulse waveform and generate pseudo-HF fluctuation in PI. LF amplitude of PRV also increased with mild body movement. This may indicate that the movement artifacts affect lower frequency band too. In this study, the subjects were office workers. They were supposed to work with the keyboard, which causes mild movement at their wrist. The reduction in HF and LF amplitude with sleep may indicate the stop of motion with dozing.

Factor analysis revealed that 83% of the variation in PRV indices was explained by two factors reflecting slow and fast variation of PRV. Interestingly, only self-reported angry was associated with an increase in factor 1 score and self-reported happiness and relaxed feeling were accompanied by increases in factor 2 score. Factor 2 mainly reflect HF amplitude and thus, increased with mild body movement and decreased with sleeping. If mild body movement indicates the good progress of work, the happiness and relaxed feeling may result from that and no increase of HF amplitude and factor 2 with angry and sadness may result from the poor progress of job accompanying the stop of working. Additionally, observation of the association between angry emotion and increased factor 1 score suggests that factor 1 may be used as an index of conflict or dissatisfaction with work.

This study has limitations. First, the subjects were office workers. Thus, the findings of this study may be specific to them. To clarify if the findings are applicable to the other job categories, further studies are required. Second, the emotion was assessed by self-reports based on a subjective feeling of strong emotions. Thus, reporting biases may have existed in the data collection. In future studies, other methods such as the random

prompts to report emotion may be required. Third, we used a wristband type pulse wave sensor attached at the wrist. If pulse wave can be measured at other places of the body that are more robust to the movement may reduce the effect of mild movement on PRV.

## V. CONCLUSIONS

The analysis of PRV obtained from wearable pulse wave sensors is increasingly used for assessing autonomic function during work. Our findings indicate that PRV thus obtained has different characteristics from those of known for HRV. Particularly, the HF component of PRV obtained by wristband type sensors may increase with mild body movement at the wrist and does not reflect cardiac parasympathetic function or resting appropriately. In contrast, a slow variation of PRV may be used as a marker of angry emotion and fast variation of PRV as that of happiness or relaxed feeling during work.

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