Design of Real-Time Autonomic Nervous System Evaluation System Using Heart Instantaneous Frequency

Yeon-Sik Noh*, Sung-Jun Park*, Sung-Bin Park ** and Hyung-Ro Yoon†

Abstract – In this study, we attempt to design a real-time autonomic nervous system (ANS) evaluation system usable during exercise using heart instantaneous frequency (HIF). Although heart rate variability (HRV) is considered to be a representative signal widely used ANS evaluation system, the R–peak detection process must be included to obtain an HRV signal, which involves a high sampling frequency and interpolation process. In particular, it cannot accurately evaluate the ANS using HRV signals during exercise because it is difficult to detect the R-peak of electrocardiogram (ECG) signals with exposure to many noises during exercise. Therefore, in this study, we develop the ground for a system that can analyze an ANS in real–time by using the HIF signal circumventing the problem of the HRV signal during exercise. First, we compare the HRV and HIF signals in order to prove that the HIF signal is more efficient for ANS analysis than HRV signals during exercise. Further, we performed real–time ANS analysis using HIF and confirmed that the exerciser's ANS variation experiences massive surges at points of acceleration and deceleration of the treadmill (similar to HRV).

Keywords: Heart Rate Variability (HRV), Heart Instantaneous Frequency (HIF), Short Time Fourier Transform (STFT), Real Time Autonomic Nervous System (ANS) Evaluation during *exercise*

1. Introduction

Recently, people's living quality has improved; therefore, interest in the early detection of diseases through checkup and preventive medicine has considerably increased. Further, the necessity of self-checkup on personal health conditions has highlighted. In particular, adult diseases such as heart diseases resulting from stress, high blood pressure, hyperlipemia, and obesity have increased considerably, so the necessity of sports medicine intended to effectively prevent adult diseases has been regarded as a critical issue. However, diseases can deteriorate by stresses experienced by the human body during exercise and also excessive exercise resulting from the exerciser's subjective decision may be fatal because of abnormal changes in the cardiovascular system. In this regard, this study investigates the prevention of accidents and proposes effectively managing exercises by enabling the exerciser to effectively analyze changes in the autonomic nervous system (ANS) according to impulses applied during exercise.

The heart rate variability (HRV) signal, which has been widely used for predicting diseases occurring in the ANS and cardiovascular system, is used to check the information on activities of the sympathetic nervous system and parasympathetic nervous system through the statistical analysis method in the time domain and element analysis in the frequency domain. The results of the study conducted by Heiko show that the cardiovascular system is influenced and heart-beat (including blood pressure) changes when mental stresses such as mathematic operations are undertaken. Further, the results show that a patient suffering from cardiovascular diseases is more susceptible than normal persons [1]–[3]. Researchers including Rollin have observed the frequency band of HRV by inducing changes in the emotional conditions during a short period of time (5 min), revealing that the proportion of LF/HF increases when the tested persons feel bad and the proportion of MF/(LF+HF) increases when the tested persons feel well [4]. However, studies analyzing changes in the ANS using the frequency band of HRV and ANS influenced by stress are conducted to observe or verify the information showing the frequency element over the entire time period. These studies may not detect changes occurring in a specific time frame. Researchers including Hong-Mo Seong have analyzed stresses occurring during specific time frames, when the stimulus is applied by an external environment, by analyzing the time–frequency relationship of the HRV signal [5].

However, we may verify the changes sensed or felt by the human body in real time when the exerciser is exercising by using only the HRV after detecting the R–

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wave of the electrocardiogram (ECG) and then performing the operation on the R–R Interval (RRI). If it is difficult to appropriately detect the R–wave because of noise expected during exercise, additional operation times are required for interpolation and also we must consider the power consumption resulting from sampling frequencies above 500 Hz for correct analysis after A/D conversion. In this regard, researchers including Barros have suggested the heart instantaneous frequency (HIF) method for acquiring the signal, which is the same as the HRV, by extracting the maximum value by analyzing the time–frequency relationship without detecting the R–wave in the ECG signal [6]. The HIF analyzes the time–frequency relationship using the ECG signal, acquired only from the human body, so the HIF enables its user to acquire data, which is the same as the HRV, even if it is difficult to detect the R–wave required when extracting the HRV signal. In addition, the HIF does not require interpolation, so the analysis time can be minimized; further, power loss of the system resulting from the high sampling frequency can be minimized. In addition, the HIF signal enables its user to analyze the frequency band instead of the existing method designed to analyze the ANS using the frequency band of the HRV, so this signal is effectively used for analyzing the ANS under specific circumstances such as exercise.

In this study, we prove the possibility of analyzing the ANS under exercise using the HIF signal by proving the identity between the HRV and HIF signals and the analysis using the HIF is more effective than the evaluation of the ANS using the HRV. Finally, we suggest a system model that enables the evaluation of the changes in the ANS sensed or felt by the human body during specific circumstances such as exercise.

2. Evaluation of ANS

2.1 ANS and HRV

The human body is controlled by the autonomic nerve playing the role of keeping the balance of the internal environment against internal and external environmental changes and anatomically classified into the sympathetic nerve and parasympathetic nerve. While the sympathetic nerve plays the role of keeping the balance of the human body and activating the physical reactions against the emergent circumstance, the parasympathetic nerve—distributed in the viscera—plays the role of keeping the smooth function by controlling the functions of the internal organs. The method of analyzing and evaluating the neurotransmitter of the ANS in the blood is considered to be the most accurate method in evaluating the ANS. However, this method is limited because the metabolic time of the ANS neurotransmitter is too short and it is difficult to actually evaluate the ANS using this method. On the other hand, the cardiovascular system sensitively reacts to changes in the ANS, so we can indirectly evaluate the cardiovascular system [7]. The HRV—the representative signal of the cardiovascular system—is widely used for evaluating the ANS and plays the important role of extracting the activity information of the ANS.

The ANS may be evaluated based on the HRV using the parameters in the time domain or in the frequency domain and a combination of these two. The purpose of this study is to evaluate the ANS under the specific circumstance during exercise, so we evaluate the ANS in the frequency domain instead of the time domain that require large amounts of time and data. Researchers have differently defined the frequency elements based on their power spectra [8]–[11]. However, we perform the research based on the frequency elements (LF: 0.01~0.08Hz; MF: 0.08~0.15Hz; HF: 0.15~0.4Hz) suggested in the study conducted to analyze the stress using the time–frequency analysis used in this study [5]. We classify the frequency bands, suggested in the study on stress, in detail for the purpose of correctly evaluating the changes in the ANS resulting from the stress applied to the human body during exercise—the final goal of this study. Further, we believe that the changes in the ANS, occurring in the human body during exercise, may be effectively evaluated by classifying the LF domain and MF domain and then excluding the interval where these two domains are influenced by each other.

2.2 HRV and HIF

As previously stated, the HRV is very effective for evaluating the ANS. However, the sampling frequency of the ECG, required for the analysis of the HRV, considerably exceeds the element range required upon analyzing the frequency of the HRV signal. As an example, the 24–h Holter system uses a sampling frequency of 128 Hz and sampling frequency for the analysis of the HRV during exercise is high—above 500 Hz. However, the spectrum response of an actual HRV for a signal sample of 1 Hz required for the HRV measurement is limited within the range of 0.5 Hz. The sampling frequency of the ECG must be decreased to resolve this problem. However, the results of the study conducted by researchers including Merri show that the precision of the HRV calculation based on the R–wave detection method is rapidly decreased together with the sampling of ECG [12].

Either the repeated signal pattern of the ECG or periodic heart rate is used to extract the HRV signal using the HIF. However, because the statistical characteristics of the HRV signal are change over time, the problem may occur in the traditional method used for measuring the instantaneous frequency, so the wavelet, which is known to be effective for the analysis of changing signals, is used for guaranteeing the validity of the data on HIF of the ECG [6].

The overview of the method used to acquire the HIF signal is as follows: The ECG signal exhibits the basic frequency if the heart rate is periodic. In this case, the power spectrum of the ECG signal consists of infinite peaks according to the harmonics of the basic frequency. However, the entire spectrum of the signal must be determined to measure the basic frequency in the spectrum response of the signal. In other words, the power spectrum must be analyzed. However, because the heart does not beat at a specific rate as that in the above assumption, a model guaranteeing the basic frequency changing according to time is required. In other words, we need to determine the heart rate or heart frequency based on the changes in respiration by classifying the respiratory sinus arrhythmia (RSA) that plays the role of modulating the ECG frequency according to changes in respiration. Frequency modulation, reported in the instantaneous frequency signal processing research program, suggests the possibility of using the concept of instantaneous frequency [13]. The instantaneous angular frequency measured in a given signal $s(t)$, namely, $\omega(t)$, is calculated using formulas (1) and (2).

$$\omega(t) = \frac{d\Phi(t)}{dt} \tag{1}$$

$$\Phi(t) = \arctan\left(\frac{-H[s(t)]}{s(t)}\right) \tag{2}$$

Here, $H[s(t)]$ is the Hilbert transform value of signal $s(t)$.

2.2.1 Correlation between HRV and HIF

The HRV and HIF signals extracted from the ECG are essentially the same. The modulation frequency that occurs when the interval between the R–waves changes according to the heart rate form the central frequency yielded by the ECG. The HIF signal expressing the change in the value by finding the maximum value of the central frequency band changing at each time through the time–frequency analysis is expressed as the signal, which is same as the HRV signal.

Further, the HIF signal shows the time series data, which is the same as the HRV signal, so this signal may replace the function provided by the HRV signal when evaluating the ANS in the frequency domain. Figure 1 shows that there is no difference in the power spectra in the frequency domain between the HIF and HRV signals. It demonstrates that the activity of the ANS may be evaluated using LF and HF, which is the most important element in this study.

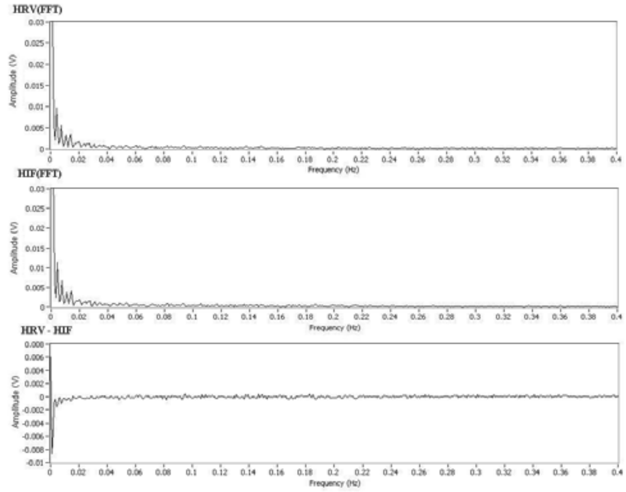

Fig. 1. Comparison of power spectra of HRV and HIF signals

3. ECG Signal Processing

3.1 Extracting the HRV by Detecting the R–wave

Nothing is more important than correctly detecting the R–wave for the analysis of the HRV signal in the ECG. We need to remove the noise and unnecessary elements other than the ECG for accomplishing this goal. In this study, we remove the power noise of 60 Hz and base–line change using a median filter of 20 points before applying the R–wave detection algorithm using LabVIEW™. In this study, we apply a variable threshold value method for detecting the R–wave [14]. The RRI signal acquired by detecting the R–wave is reorganized as the RRI signal by re-sampling process performed at 4 Hz for correct analysis.

3.2 Extracting the HIF

Researchers including Barros have suggested a new method using the instantaneous frequency for the purpose of acquiring the HIF signal, which is the same as the HRV signal [8]. Therefore, many studies have been conducted to acquire better HIF signals [15][16]. However, the basic framework of earlier studies is maintained, so we use the extraction process used in the earlier studies and process the signal after making a minor modification to the test environment and variable of the experimental value under consideration. First, we remove the power noise of 60 Hz and then base line changes using a 20–point median filter before processing the signal for the acquired ECG as done when extracting the HRV signal. We perform down-sampling by compressing the ECG signal into 10 Hz after removing the power noise and base–line changes and increase in the cutoff frequency from 1.7 Hz to 3.6 Hz, which is acquired through the test. The filtered signal is processed through the STFT process for a short period of time. The STFT method introduced by Gabor is useful for the time–frequency analysis. This method guarantees high resolving power appropriate for this study using the instantaneous frequency [17]. Gabor divided the entire signal $x(t)$ into many small intervals using a window $h(t)$ assuming that each interval occupied by each window is stable and then Fourier conversion is applied to each interval. In other words, the time dependency is provided by classifying the whole signal into many small intervals. The Fourier conversion is conducted only in the interval where $h(t)$ is applied to $x(t)$. The frequency element applied to each interval showing the time dependency is acquired by repeatedly moving the window over the entire signal. However, the STFT results show that there is a considerable difference between the resolutions in the time domain and frequency domain according to the selected window function, so the type and size of the window are selected according to the characteristics of the signal and signal–acquiring environments [18][19]. The STFT is expressed as follows.

$$X_{STFT} = \int x(\tau) h^*(\tau - t) e^{-2\pi f t} d\tau \qquad (3)$$

The spectrogram from the STFT acquired through the above procedures (formula (4)) can be determined. Figure 2 shows the examples of the spectrogram acquired from the ECG under a stable condition and exercise condition.

$$spectrogram(t, f) = \left| STFT(t, f) \right|^2 \qquad (4)$$

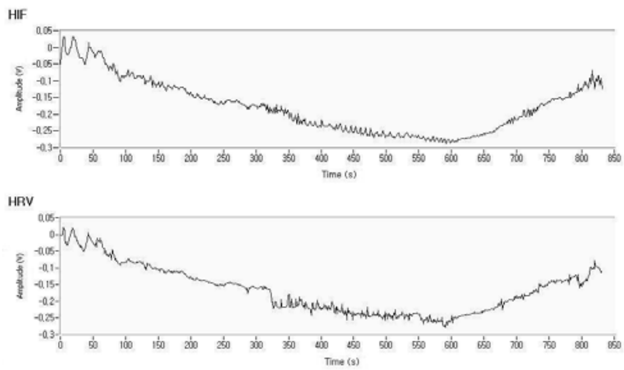

Fig. 2. HRV signal (measured when the R–wave is appropriately detected) and HIF signal

4. Test and Discussion

4.1 Configuring the Hardware

The arm-bending–type hardware is designed and fabricated focusing on being light weight and compact to eliminate inconvenience during exercise. This hardware is designed to concurrently acquire the ECGs of two channels and measure the activity of two axes (X-Y). The signal processing system is configured to process the transmitted data via a PC. The system power is designed to cover up to 30 exercisers without additional charging in consideration of the average exercise times of persons using the treadmill in the fitness club based on the average number of users of each treadmill for each day.

4.2 Test Process and Configuration

We perform the test for 12 healthy men (average age ± SD: 28.4 ± 0.97) after obtaining prior consent. We selected healthy persons without cardiovascular diseases such that they were suitable for the ANS evaluation system development goals under the intention of proving that the HIF signal may be used for the evaluation of the ANS instead of the HRV signal and acquiring stable data. We perform the test for the purpose of proving the similarity of HRV and HIF by processing the signal after saving the ECG signal transmitted from the human body during the exercise and then verifying that real–time ANS analysis data, acquired from the HIF signal through the test, is clinically valuable as the HRV signal.

4.3 Comparison of HRV and HIF during Exercise

We compare the data acquired when the R–wave of the ECG signal is inappropriately and appropriately detected during exercise. The R–wave is not detected because of noise expected during exercise. The detection of R–waves depends on the performance of R–wave detection algorithm.

4.3.1 Comparison of HRV Signal (Measured when R–waves are Appropriately Detected) and HIF Signal

In this section, we prove that the HIF signal can be used for the evaluation of the ANS instead of HRV signal by comparing the HRV and HIF signals appropriately expressing changes of the ANS. Figure 2 shows the HRV signal acquired from the ECG signal effectively detecting the R–wave and HIF signal. While the HRV signal indicates the RRI information acquired after detecting the R–wave from the measured ECG, the HIF indicates the time signal by extracting the maximum value through the STFT process. These two signals are quantified and then expressed in size for an exact comparison. Table 1 shows the correlation diagram between the HRV and HIF signals acquired from the data where the R–wave is effectively detected from 7 tested persons out of 12 persons.

Table 1. Correlation diagram of HRV signal (measured when the R–wave is appropriately detected) and HIF signal

Subject	R^2
A	0.791
B	0.971
C	0.959
D	0.982
E	0.920
F	0.798

4.3.2 Comparison of HRV and HIF Signals when No R–waves are Detected

The HRV signal that cannot appropriately detect the R–wave is not useful in the ANS evaluation. As previously stated, the HIF signal may replace the HRV signal when evaluating the ANS; further, the HIF signal may be used even if the R–wave of the ECG signal is not detected during exercise, so this result shows that the analysis using the HIF signal is superior to the HRV signal. We determine the ECG of the tested persons when the R–wave is effectively detected for the comparison of the signals and then add white noise for interrupting the detection of the R–wave in the ECG signal. Table 2 shows that the HRV signal is rapidly distorted when the signal–to–noise ratio (SNR) becomes 11 dB by increasing the amplitude of the added white noise. The R–wave detection error rate shows the relative difference from the number of detected peaks in the original signal. This difference indicates that a wrong peak is misunderstood as the R–wave or missed when the size of white noise increases. Figure 3 shows the ECG, HRV signal and HIF signal when the SNR becomes 11dB against the white noise. The figure shows that the HRV signal is more distorted than the HIF signal.

Table 2. Correlation between signals when the original signal and white noise are inserted and R–wave detection error rate

SNR (dB)	R^2 HIF – HIF (when noise is added)	R^2 HRV – HRV (when noise is added)	R–wave detection error rate (%)
14	0.957	0.828	0.577
12.5	0.929	0.827	0.041
11	0.806	0.208	4.783
10	0.719	0.086	10.309
9	0.592	0.063	12.288
8	0.472	0.017	14.391

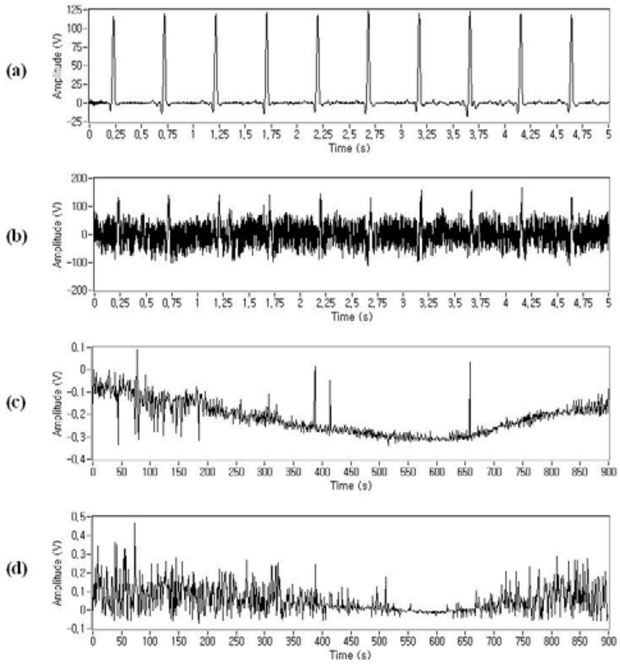

Fig. 3. HIF and HRV signals after white noise is inserted when the SNR becomes 11 dB
(a) Original ECG signal
(b) ECG when white noise is added
(c) HIF signal (d) HRV signal

4.4 Performance Evaluation

4.4.1 Comparison of Time Required for Performing the Program

The method for extracting the HRV signal using the HIF signal is superior because the R–wave is not detected and the program can be performed within a short period of time. The process of acquiring the HRV signal after acquiring the HRV from the ECG takes a long time because the processes of detecting the R–wave and interval between the R–waves and removing the linear element and interpolation works are added. Table 3 shows the compared times required for the performance of the HRV and HIF methods in the ECG signal measured against 12 subjects. This table shows that the HRV analysis method requires 30 times more time than that required by the HIF analysis method.

4.4.2 Comparison of Performance Measured when the Sampling Frequency is Changed

High sampling frequencies of above 500 Hz are required for appropriately acquiring the HRV signal from the ECG signal during exercise. Such frequencies are required for correctly measuring the time when the R–wave occurs in the process of detecting the R–wave of the ECG during exercise. Incorrectly measured time resulting from a low sampling frequency induces an error in the RRI value required for HRV analysis, so correct changes in the ANS during exercise cannot be expressed. Table 4 shows the correlation coefficients when the original signal is sampled at 500 Hz and decreasing the sampling frequency from 250 Hz to 125 Hz. The HIF signal is not related to the sampling frequency. However, the HRV shows substantial difference when compared with the HIF. This value is not large in terms of its numerical value. However, this difference is large in consideration of the error expected when analyzing the ANS resulting from the change in the RRI value.

Table 3. Comparison of times required for performing HRV and HIF (based on the LabVIEW^{TM} timer)

Subject	Time required for performing the HRV (s)	Time required for performing the HIF (s)
A	7.766	0.226
B	4.609	0.235
C	7.843	0.281
D	7.782	0.234
E	7.797	0.235
F	6.549	0.234
G	8.234	0.266
H	8.531	0.234
I	7.432	0.250
J	7.752	0.229
K	8.125	0.230
L	7.769	0.238

4.5 Real–Time Evaluation of ANS Using HIF Signal

This test is conducted to evaluate the ANS instead of using existing methods that use the HRV signal. The results of this test show that the HIF signal enables real–time analysis of changes in the ANS occurring during exercise when it is difficult to acquire the R–wave because the HIF signal is closely related to the HRV signal. We may indirectly check the changes in the ANS resulting from the external stimulus applied to the human body at each interval where the treadmill speed is changed by analyzing the HIF signal.

We analyze the changes in the ANS by analyzing the frequency band through the FFT of the HIF signal extracted from the ECG signal acquired during exercise. We observe how the frequency band elements (LF and HF) of the HIF signal change in terms of size by increasing treadmill speed. We configure the test procedures of 15 min such that 5 min each are allocated for walking, running, and walking (in this order). We increase the stimulus applied to the human body by letting the exerciser slowly walk at a speed of 3 km/h for the first 3 min and then quickly walk at a speed of 4.5 km/h for another 2 min. We maximize the activity of the sympathetic nerve by letting the exerciser run at a speed of 7 km/h for the first 2 min and then quickly run at a speed of 8.5 km/h for another 3 min to increase the burden on the human body. We induce antagonism of the ANS by letting the exerciser walk at a speed of 4 km/h for the first 3 min and then walk at a speed of 1 km/h for another 2 min.

We do not analyze the frequency to collect the data to be used for the analysis for the first 3 min and then observe the transition occurring during the exercise by calculating the LF/HF ratio every 2 s after 3 min. 0.24 s is required for analyzing the HIF signal measured against 12 subjects on an average, so we can theoretically perform the analysis every 0.3 s. However, we perform the analysis every 2 s in consideration of the user’s convenience. The test results reveal that the LF/HF ratio increases rapidly in the interval where the speed abruptly increases and also the test results show that the LF/HF ratio decreases and then gradually increases by antagonism of the ANS in the interval where the speed decreases. This result proves that the HIF changes according to changes in the ANS as the existing HRV analysis method. In addition, the HIF analysis method guarantees that changes in the ANS occurring during exercise can be verified in real–time and the level of stimulus (exercise strength) applied to the human body can be visually checked at each speed interval based on the results of existing studies [8][10], revealing the possibility of evaluating the ANS by means of analyzing the frequency of the HRV and analyzing the signal resulting from cerebrovascular diseases. In addition, this result implies that by statistical analysis, the occurrence of cerebrovascular diseases might be predicted. Figure 4 shows the final waveform indicating that the LF/HF ratio changes during exercise and ANS considerably changes in the interval where the speed decreases rapidly after running at a brisker speed.

Table 4. Correlation diagram of each signal measured when the sampling frequency is changed

	HIF (R^2)	HRV (R^2)
500Hz	-	-
250Hz	0.9999281	0.9995002
125Hz	0.9998689	0.9647307

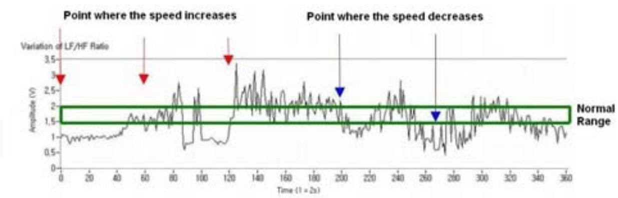

Fig. 4. Analysis of ANS using the HIF signal

5. Conclusion

In this study, we develop a novel HIF–based method to evaluate the ANS instead of using HRV under circumstances when it is difficult to detect the R–wave from the ECG signal such as during exercise. The operation process of the HIF–based ANS analysis method is simpler than many existing methods using the HRV signal, so the time required for acceptable performance is short and more effective for analyzing the frequency domain of ANS by down-sampling at 10 Hz.

The HRV signal—widely used for the analysis of stress—is used to acquire high–level data if the subject is in a steady state. However, this signal requires a high sampling frequency (exceeding 500 Hz) during the exercise; further, this signal may be acquired only after performing complicated processes such as R–wave detection algorithm, detection of interval between R–waves, and interpolation of the interval where the R–wave is not detected, so it is difficult to analyze the ANS during exercise in real time even if a high-performance microcontroller is used.

In this regard, we verify the correlation between the HRV and HIF signals for the purpose of proving that the ANS may be analyzed using the HIF signal instead of using HRV. The results show that the correlation coefficient (R^2) is determined to be 0.952 and the HRV and HIF signals are closely related when the R–wave can be conventionally determined. The HRV signal is clearly detected when all the R–waves are detected without any loss, so the fact that the correlation coefficient between the HRV and HIF signals is high indicates that the HIF signal may replace the HRV when the R–wave is correctly detected. In addition, the method using the HIF is about 30 times faster than the one using the HRV with regard to the operation performance time (based on LabVIEW™ operation processing time). Also, the HIF signal acquires the signal by processing the signal acquired by down-sampling at 10 Hz in the beginning, so this signal does not require a high sampling frequency.

However, the HIF–signal–based ANS analysis method may not assume the statistical changes in the time domain which is obtainable using the HRV signal because this method may not acquire the statistical information from the HIF signal using the information of the interval between the R–waves. Further, there may be some differences between the values acquired by analyzing the ANS through the analysis of the HIF–signal–based frequency band elements (LF/HF ratio) and the value acquired by including the time domain and frequency domain.

However, the HIF signal may effectively evaluate the ANS instead of the HRV. This study is meaningful in terms of continual and effective health care and preventing accidents by developing ubiquitous and health–care–based mobile and compact systems.

In addition, the accomplishments of this study reveal a better method to measure the heart load than that done by existing methods using VO_{2MAX}, HR, and HRV signals without being dependent on the place or equipment if the ANS analysis method through the HIF suggested in this study is applied as a parameter when measuring the heart load as a part of a future project.

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