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ORIGINAL ARTICLE

Optimized Exercise Load Control System Based on Heart Rate Variability

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Abstract
Purpose The purpose of this study is to present method of providing optimal physical exercise effect using Heart Rate Variability (HRV; LF/HF Ratio) during step-by-step exercise load.
Methods In general, when physical exercise is started, heart rates and cardiac outputs tend to increase owing to increasing muscular activities. This study used HRV as an input parameter for optimized exercise load control, as it can reflect fluctuation of autonomic nervous systems. In addition, HRV was measured in real time while performing aerobic exercises to verify effects of HRV.
Results Multiple-input and single-output (MISO) PID system with HRV showed the best performance in terms of exercise load stability (Damping parameter). In terms of exercise loads by system, the MISO PID System had the widest coverage among the three systems, which mean that given physical exercise would bring the most efficient exercise load and workout for each subject. From the result, two important facts were deduced: First, when the subjects engaged in the same type of physical exercise, they would get the most out of workout while remaining in the target zone when using the MISO PID control system. Second, the system showed the smallest variation in terms of exercise load (Manual System: 146±5.99; SISO PID System: 147±6.92; and MISO PID System: 151±3.18, $p<0.001$), the subject could perform physical exercise with minimal heart load.
Conclusions When using HRV as control the system, it was possible to provide more stable exercise load to users automatically and get maximum exercise effects through minimal heart load.

Keywords Optimized exercise load control system, HRV, PID control, Heart rate, Exercise load

INTRODUCTION

Physical exercise is effective in preventing and treating habitual illnesses and promoting health through increasing stamina. However, unsuitable physical exercise always involves danger and sometimes may personal health worsened. Thus, physical exercise shall be performed carefully. For appropriate exercise, it will be considered that individual physical condition, physical fitness, age and goal of exercise [1, 2]. Also scientific management of physical exercise programs includes a selection of exercise type or quantitative and qualitative coordination of exercise. Owing to such demands, there have been many studies engaged in development of systems or algorithms to provide optimized exercise load.

Purpose of physical exercise is to promote personal health, increase fitness and prevent illnesses. To promote health and improve physical fitness, it is important to perform regular and well-regulated physical exercise [3], as improved physical activities will enrich personal life and well-being. Exercise load is consisted of five essential elements: frequency, intensity and duration of exercise, type of physical activity and progressive enhancement [4].

The five essential elements of each person will enhance personal competency [5, 6]. Muscular strength and endurance enhanced through increased regular and proper physical exercise will be of great help in promoting health [2]. In addition, the weak and the elderly may strengthen their bones through proper level of physical exercise which will help in reducing minerals owing to aging and preventing

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osteoporosis. In spite of such benefits, there are not many people who do physical exercise by estimating optimal exercise load fit for their individual need. Actually, to estimate optimal exercise load, it is necessary to perform a series of complex tests including fitness test, questionnaire examination and exercise test.

Among the recent researches on providing optimized exercise load to users, there was a system using Hip Tracker presented by Lee Lichtenstein who presented how to help visually impaired persons perform physical exercise using the distance from hip to tracker [7]. However, such method using automatic provisioning of physical exercise based on location data of subjects has its limitation, as it cannot make users to perform more physical exercise in general, and is difficult to check physiological signals of the users.

Thus, this study presented a control method which can present exercise load optimized for each user automatically by checking his/her physiological changes objectively. To check physiological changes, Heart Rate (HR) and Heart Rate Variability (HRV: LF/HF Ratio) representing influence of autonomic nervous system were analyzed in real time.

Continuous electrocardiograph monitoring of the heart is routinely done in many clinical settings, especially in critical care medicine. Commercial heart rate monitors are also available, consisting of a chest strap with electrodes. The signal is transmitted to a wrist receiver for display. Heart rate monitors allow accurate measurements to be taken continuously and can be used during exercise [5]. And the maximum heart rate (HRmax) is the highest heart rate an individual can safely achieve through exercise stress, and depends on age.

Heart rate variability is thought to represent the autonomic balance between the sympathetic and parasympathetic pathways acting on the intrinsic rhythm of the sinoatrial node of the heart [8]. The most commonly used indices of HRV simply use statistics derived from the intervals between R-R complexes on the electrocardiogram. The study of HRV has evolved with time series spectral analysis. In the frequency domain, human HRV spectra have displayed 2 or more major harmonic components. One is at frequency > 0.15 Hz, mediated solely by changing levels of parasympathetic nervous system (PNS) activity. The other components are usually seen at or below 0. 1 Hz and are coherent with blood pressure variability. It has been demonstrated that the latter components at frequencies < 0.15 Hz might be associated with both sympathetic nervous system (SNS) and PNS activities [8, 9]. The relative power of each point in the frequency domain can be obtained. The frequency domain is identified as HF (0.15-0.40 Hz); LF (0.04-0.15 Hz). The LF/HF ratio has been commonly accepted to be a reflection of autonomic balance [10]. Based on influence of these parameters, the necessity of exercise load system using HRV and its effect on physical exercise was assessed.

METHODOLOGY

Subject

Tests were performed to 12 healthy males (26.9 ± 3.2 years in age). All subjects have no records of cardiovascular diseases. All subjects received a presentation on test procedure, i.e., test protocol, before the tests. After the presentation, they were required to sign a consent form with instructions to prevent any possible accident during the test. All subjects were in restrained rules such as taking hard exercise, alcohol, smoking and caffeine for 12 hours before the test. 12 healthy males were strictly to minimize influence of caffeine or physical exercise on physiological signals to be used in assessing exercise load [11].

Test method

As shown in Fig. 1, each subject wore fabric electrodes and the embedded bioinstrumentation system on his chest to measure physiological signal, and then performed physical exercise protocol as shown in Fig. 2.

Subjects reclined comfortably in chairs as shown in Fig. 2 and measured heart rates and HRV for five minutes in resting state. Since the subjects were restrained from taking severe physical exercise, alcohol, smoking and caffeine, physiological signals measured in resting state clearly revealed physical conditions of the subjects in stable state. Biometric data obtained in this state would act as an element in bio-

Fig. 1. Sensor placement.

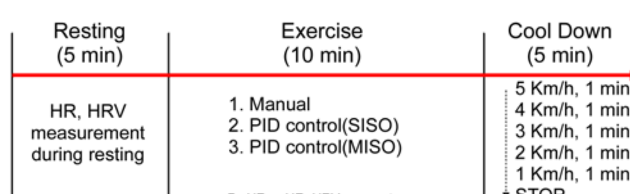


Fig. 2. Exercise Protocol.

feedback for providing initial target HR and HRV during physical exercise.

In exercise state, the system provides optimized exercise load (speed) automatically to the subjects by using measured physiological signals. The control system also got feedback of heart rate and HRV of the subjects automatically in real time to affect providing exercise load which is treadmill speed.

In cool down state after terminating physical exercise, the system played a role of warming down pulse rates and respiration of the subjects to normal level slowly.

Testing equipment and analysis

For this study, a system was designed to provide exercise load (treadmill speed) to users automatically based on various physiological changes detected during physical exercise as shown in Fig. 3.

The features of the system are as follows below

First, the wearable electrodes were used for detecting physiological changes in convenient activity of the subjects. These electrodes provided unrestrained environment for the subjects in acquiring required data [12].

Second, as shown in Table 1, embedded bio-instrumentation system was used to transmit and process physiological signals obtained through the wearable electrodes [13]. The embedded bio-instrumentation system was designed to facilitate portability and movement of the system while performing physical exercise by the subjects.

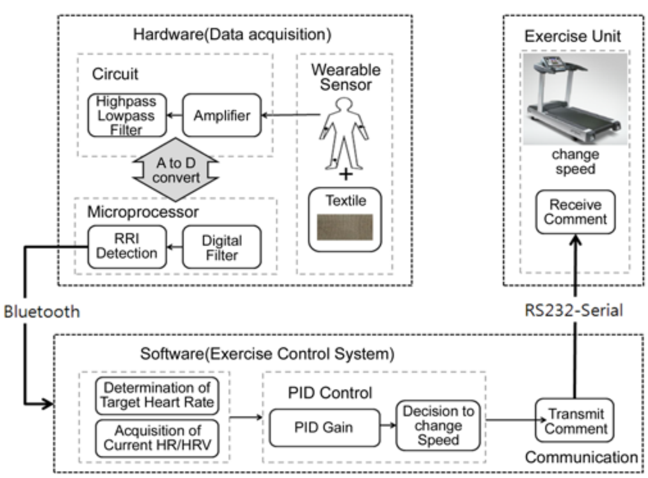
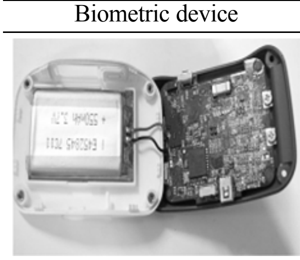


Fig. 3. Data acquisition and data processing

Table 1. Biometric device specification.

Biometric device	Specification
	· ARM 32-bit Cortex M3 CPU 36 MHz maximum frequency · 1CH ECG(lead I): 500 s/Sec · 3 axis accelerometer · Bluetooth class 2

Third, exercise load was estimated by using physiological signals acquired with the wearable electrodes and the embedded bio-instrumentation system. Appropriate exercise load was calculated by using detected physiological signals as control parameters in real time. For the optimal exercise load, we have to figure out the capacity of individual. VO2max is the maximum capacity of an individual's body to transport and use oxygen during incremental exercise which commonly reflects the physical fitness of the individual [14]. However, the protocol of VO2max is very difficult that user wants to know the capacity of an individual's body. Thus, this study used that the Karvonen method factors in resting heart rate (HRrest) to calculate target heart rate (THR), using a range of 50–85% intensity [14]. As shown in Eq. (1), the American College of Sports Medicine (ACSM) provides this equation for low the capacity of an individual [5].

$$HR_{max} = 220 - age$$
$$THR = ((HR_{max} - HR_{rest}) \times \%\ intensity) + HR_{rest} \quad (1)$$

Additionally, the optimal frequency ratio in HRV (LF/HF) was estimated. Low frequency (LF: 0.04-0.15 Hz) representing combined sympathetic and parasympathetic modulations. And high frequency (HF: 0.15-0.4 Hz) reflecting parasympathetic modulations and the influence of respiration [8]. Therefore, the optimal LF/HF ratio was estimated that the balance's factor of interaction between sympathetic and parasympathetic is ratio=1.02 [14].

Fourth, the signal processing procedure for data acquisition used band pass filter, median filtering, and moving average filter. It is difficult to get bio-signals which are HR(R-R peak) and HRV(5 min) during physical exercise. For acquiring bio-signals, the band pass filter (0.02 Hz-30 Hz) in R-peak detection helps to remove power noise and movement artifact as shown in Fig. 4. The median filter in R-peak detection assists to detect r-peak from subject. And base-line elimination effectively removes respiration signal as the moving average filter.

Finally, relationships between target heart rate and current heart rate, and HRV to trace changes in nervous system were added to facilitate estimation of exercise load. Heart rate was used widely to understand current physiological state of body, but the MISO PID system added HRV data, an indicator of autonomic nerve system. And HRV data help to check the states of both sympathetic nerves and parasympathetic nerves in real time and used it as an element in controlling exercise load [15-17]. In Fig. 5, this shows input parameter is the difference between target HR & HRV and current HR

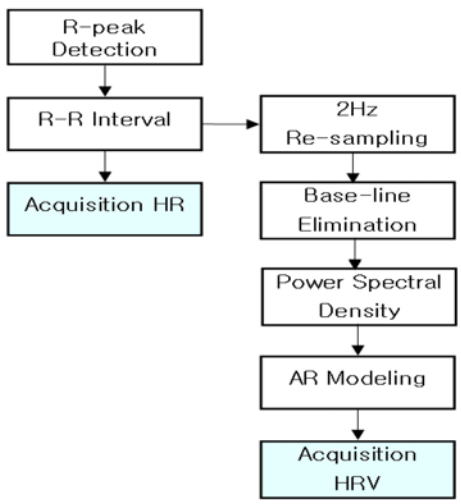


Fig. 4. Signal processing procedure.

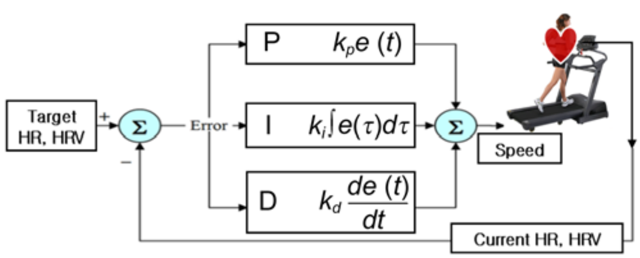


Fig. 5. The equation and diagram of MISO PID system.

& HRV in real time. The biometric device can acquire the bio-signals (current HR, HRV) in real time during the early stage and physical exercise. MISO PID system which is closed loop provides a treadmill speed by the difference between bio-signals. The bio-signals in subject on treadmill were changed by treadmill speed. After, the changed bio-signals (current HR, HRV) are used for next input parameter.

RESULTS & DISCUSSION

All data are presented as mean±SD. Statistical analyses were conducted using the statistical package for the social sciences software. Data was established using One-way ANOVA statistic.

First of all, the study checked mechanism of exercise control reaction when providing exercise loads to the

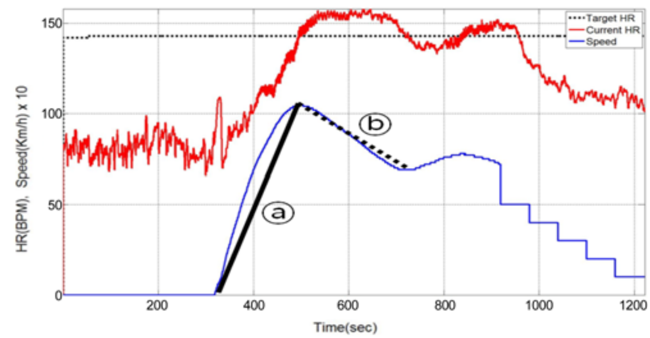


Fig. 6. System Model Comparison (ⓐ Response time, ⓑ Damping)

subjects automatically by using the MISO PID system with HRV (LF/HF Ratio). In this way, by checking damping parameters during and after reaction, the influence of HRV to the reaction to athletic equipment could be verified.

According to physiological signals in Fig. 6, ⓐ shows reaction time of treadmill and ⓑ shows Over-damping and Under-damping feed back after reaction.

Manual System was designed to control by the subjects based on displayed target heart rate by regulating speed by themselves according to differences in heart rate. As shown in Table 2, this system shows faster exercise load reaction caused by passive control by the subjects, but owing to numerous occurrence of damping, the subjects had to raise or lower the speed repetitively.

A Single Input Single Output (SISO) PID system provides exercise load automatically by using HR. Although this system can show faster exercise load control reaction than a Multiple-Input And Single-Output (MISO) system, damping phenomena would occur more frequently. This is because the MISO system using HRV as an additional input can provide exercise load information more stably as it analyzes reactions of autonomic nervous system to find appropriate exercise intensity point and use it as an exercise load control (speed control). As a result, it could provide information on exercise load most efficiently and safely to the subjects when the system was controlled by changing input parameter (HRV) of nervous system generated during physical exercise.

Second, the study compared the treadmill speeds in each system model and heart rates of the subjects. As shown in Fig. 7, each system model showed distinctive physical exercise pattern. Integrated value of a changed speed curve (blue-line) of the treadmill means the volume of physical exercise by a

Table 2. Response time each system and damping parameter.

Variables Index	Manual System mean (±SD)	Single i/o PID System mean (±SD)	Multiple input/ single output PID System mean (±SD)
All Subjects Response time	1.42 (0.52)	0.67 (0.18)	0.56 (0.18)
All Subjects Damping parameter	-0.5 (0.15)	-0.15 (0.06)	-0.11 (0.03)

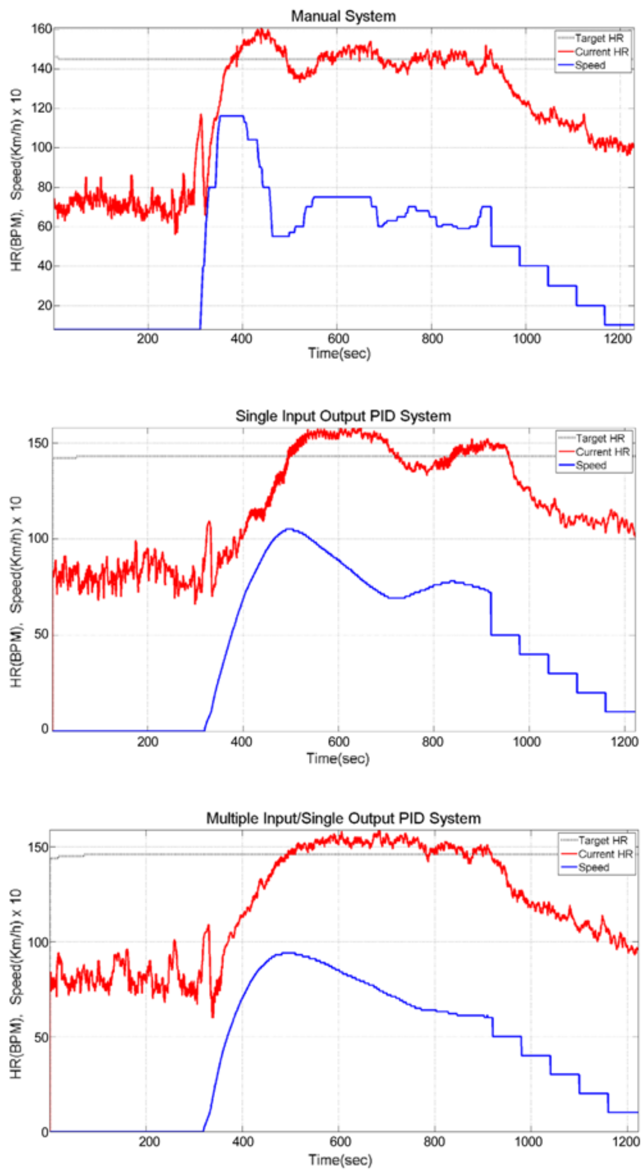


Fig. 7. Change in exercise tolerance by the system.

subject.

The difference of SISO PID system and MISO PID system is that MISO PID system has the target zone of LF/HF ratio, one of HRV parameters. From this, exercise load of the MISO PID system with HRV increased 11.01% (coverage of the speed curve) compared to the SISO PID system dependent on heart rate in Table 3. It means that a system using HRV as an additional element can perform more volume of physical exercise in the same duration than the other model, thus it is a more efficient model.

Third, the study compared the change of heart rate in each system model during physical exercise. As shown in Fig. 8, when the speed of athletic equipment is controlled by the MISO PID system as finally presented in this study, it was confirmed that the current heart rates of the subjects would be controlled uniformly during physical exercise. Maintaining heart rate uniformly at optimal exercise intensity means that current physical state of each person was feed back to regulate exercise intensity appropriately, and the subjects performed the physical exercise most efficiently without

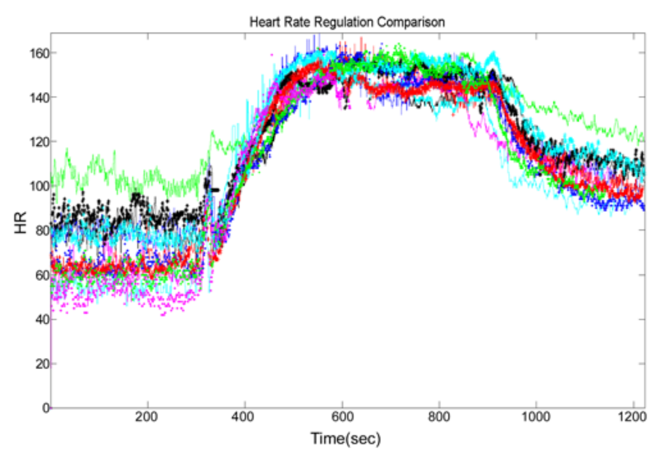


Fig. 8. Heart Rate Regulation Comparison.

Table 3. The coverage of the speed curve ratio and analysis (P < 0.001).

Speed

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	8501	57.7535	21.66549	.23498	57.2929	58.2142	9.36	94.08
2	8501	62.7928	28.70692	.31135	62.1825	63.4031	9.19	105.07
3	8501	64.1171	24.22539	.26275	63.6021	64.6322	10.90	116.04
Total	25503	61.5545	25.18433	.15770	61.2454	61.8636	9.19	116.04

(1: Manual system, 2: SISO PID system, 3: MISO PID system)

Speed

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	191678.252	2	95839.126	152.906	.000
Within Groups	15982975	25500	626.783		
Total	16174653	25502			

heavy heart load caused by changing exercise intensity.

The first five minutes in Fig. 8 showed that heart rate was relatively low in resting state, and was progressively increasing following gradual increase of exercise intensity. A noteworthy point is that the system controlled speed of the athletic equipment automatically to reach the target heart rate. As a result, it means that the exercise load control system identifies current status in real time and changed exercise load to an appropriate level for the subjects automatically.

In addition, as shown in Table 4, the system providing exercise load based on added HRV displayed relatively low LF/HF ratio than the other systems. This means that the MISO PID system focused on given physical exercise more efficiently and performed physical exercise more stably without physical and psychological overloads. The change of HRV is LF component becomes dominant, but as total variance is reduced, the absolute power of LF appears unchanged during exercise. Normalization procedure leads to predominant LF and smaller HF components, which express the alteration of spectral components due to exercise [14]. The situation to change biological effect gives a stable exercise load.

Table 5 shows features and functionalities of the existing system model and the MISO PID system, an optimal exercise load system presented in this study. When checking heart rate regulation with standard deviations of heart rate (heart rate turbulence), values out of the MISO PID system is distributed tightly around the target heart rate. From this, the fact that exercise load was provided stably to the subjects during physical exercise. The tightly around the target heart rate in MISO PID system means that user on MISO PID system didn't have the heart rate turbulence. When comparing exercise loads between the systems, the MISO PID system showed 46% less exercise load (heart rate turbulence) than Manual system.

CONCLUSION

The purpose of this study is to show that when using HRV

Table 4. All subjects' Heart Rate Variability Ratio ($P < 0.001$).

HRV_Ratio

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	4056	1.8281	.80888	.01270	1.8032	1.8530	.72	4.09
2	4056	1.5785	.62221	.00977	1.5594	1.5977	.63	3.88
3	4056	1.1762	.61714	.00969	1.1572	1.1952	.00	4.66
Total	12168	1.5276	.73902	.00670	1.5145	1.5407	.00	4.66

(1: Manual system, 2: SISO PID system, 3: MISO PID system)

HRV_Ratio

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	877.551	2	438.775	925.500	.000
Within Groups	5767.374	12165	.474		
Total	6644.925	12167			

Table 5. All subjects' Heart load during exercise ($P < 0.001$).

HR

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	4056	146.6643	5.99595	.09415	146.4797	146.8489	132.77	161.47
2	4056	147.5697	6.92921	.10880	147.3564	147.7830	132.96	158.16
3	4056	151.0511	3.18483	.05001	150.9530	151.1491	140.84	159.22
Total	12168	148.4283	5.91106	.05359	148.3233	148.5334	132.77	161.47

Variables Index	Manual System	Single i/o PID System	Multiple input/ single output PID System
All subjects Heart Rate Standard deviation	5.99	6.92	3.18
Exercise tolerance load comparison	15% Increment (Manual system / Single system)		
		46% Decrement (Manual system / MISO system)	

(LF/HF Ratio) as a control element in providing exercise load progressively, the system provides optimized exercise effects. This study verified that if HRV was used as an element of exercise load control system during physical exercise, the system provided exercise load more stably and efficiently than the other systems. Also, the system provided larger volume of physical exercise to the subject in the same time span with less variation of exercise load.

In conclusion, the MISO system using HRV provided a more stable exercise load to subject. The reason for stable exercise load is that the changed HRV by exercise is going back to input parameter as closed loop. When performing the same type of physical exercise in same duration with the three systems, the MISO PID System with HRV would provide targeted more optimal physical exercise for the subjects than the other systems with less heart load (46% decrement). And the MISO PID system had the widest exercise quantity(speed curve) among the three systems, which mean that given physical exercise would bring the most efficient exercise load (11.01% increment).

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