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Personalized heart rate management through data-driven dynamic exercise control

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Maximizing healthy life expectancy is essential for enhancing well-being. Optimal exercise intensity is crucial in promoting health and ensuring safe rehabilitation. Since heart rate is related to exercise intensity, the required exercise intensity is achieved by controlling the heart rate. This study aims to control heart rate during exercise by dynamically adjusting the load on a bicycle ergometer using a proportional-integral (PI) control. The choice of PI parameters is very important because the PI parameters significantly affect the performance of heart rate control. Since the dynamic characteristics of heart rate relative to work rate vary widely from subject to subject, the PI parameters for each subject must be determined individually. In this study, PI parameters are optimized directly from exercise data using a data-driven design approach. Thus, the proposed method does not require excessive exercise of the subject to model heart rate dynamics. Using the proposed method, the heart rate can be controlled to follow a designed reference model so that the heart rate is safely increased to the desired value. The quantitative evaluation of the control results of fifteen healthy volunteers confirmed that the proposed method improved the control error of the target heart rate trajectory by approximately 40%, regardless of gender or age. In addition, it was shown that control parameters from the exercise experiment also indicate that females are more likely than males to have an elevated heart rate at the same load.

Longevity enhances human prosperity but also leads to increased medical costs[1,2]. One solution to this challenge is to extend healthy life expectancy, and exercise of appropriate intensity is effective not only in extending healthy life expectancy but also in providing safe rehabilitation[3–8]. Since heart rate is related to exercise intensity controlling heart rate allows one to achieve the required exercise intensity[9]. In recent years, heart rate can be easily measured with a variety of devices, allowing one to determine for oneself the appropriate intensity of exercise[10]. However, constantly monitoring the ever-changing heart rate in response to exercise and adjusting the exercise load is tedious and does not improve motivation to exercise. In addition, it is actually difficult for not only frail or sickly people but also healthy people to adjust themselves to an appropriate load according to their heart rate.

Exercise equipment such as bicycle ergometers and walking treadmills are used in the welfare and medical fields to exercise at the required intensity[11–13]. An ergometer is an equipment on which the subject pedals, while a treadmill is an equipment on which the subject walks on a conveyor belt at a controlled speed. Both equipments allow the subjects to exercise appropriately, while one of the features of the ergometer is that it allows people who have difficulty walking independently, which is not possible on a treadmill, to exercise safely[14–16]. The purpose of this study is to control the heart rate of subjects using an ergometer to provide the necessary exercise intensity for a wide range of people, thereby achieving the well-being of people in the world.

Similar to the purpose of this study, there are studies that automatically adjust the heart rate of subjects using an equipment that can vary the load given to the subject[17]. In heart rate control, it is important not only to achieve the target heart rate at steady state, but also to have a transient response to safely raise the heart rate.

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To this end, several methods have been proposed to automatically control the heart rate using an ergometer with variable load[18–26]. In Ref.[18], the heart rate of a subject is controlled using the proportional-integral (PI) control method. Since this method requires a transfer function from work rate to heart rate to determine the PI parameters to be used in the experiment by numerical simulation, a subject is given a pseudo-random binary sequence of numbers to identify the transfer function. However, pseudo-random binary sequences can be very taxing on subjects because the load changes abruptly and repeatedly. While optimal control is designed based on a discrete-time linear time-invariant system model[19], sliding mode control using a time-varying system model has also been proposed[20]. A dynamical system of the heart rate response to exercise intensity is identified as a nonlinear quadratic system[27], and nonlinear control methods are proposed[21–23]. In contrast to the time domain design, the model-based input sensitivity function from disturbance to work rate is designed in the frequency domain[24,25]. The frequency-domain design methods are based on a model of a first-order system, and its design based on a second-order delay system has improved control performance[26]. Because these frequency-domain designs are also based on models identified using pseudo-random signals[28,29], the burden on the examinee during model identification remains high. However, such excessive exercises for modeling by subjects should be avoided.

This study proposes a method for controlling heart rate that does not require excessive exercise for modeling. In this study, a heart rate control system is developed by providing the subject with a work rate determined by PI control via an ergometer. Since the dynamic characteristics of heart rate relative to work rate vary widely from subject to subject, the PI parameters designed for one individual may not be appropriate for another. Therefore, since the PI parameters must be determined for each subject, a heart rate controller is designed for each individual subject exercising on the ergometer using data-driven control[30–32]. Since this design method is based on the model reference problem, the transient and steady-state responses can be controlled by adjusting the time constant of the reference model to safely increase the heart rate.

Although model-based design has the advantage of enabling robust design and predictive control because the dynamic characteristics of the target system can be understood[33], its control performance is highly dependent on the accuracy of the identification model, and the modeling work is complex. In contrast to the model-based approach, the data-driven approach designs controllers directly from data without the use of models[34,35], which is expected to reduce the excessive exercise for model identification required in model-based design.

A heart rate experiment was conducted on fifteen healthy volunteers using the control system designed and created in this study. The results of the experiment on male and female subjects in their 20s to 50s confirmed the validity of this study. In addition, it was confirmed that:

1. The heart rate trajectory is dominated by integral compensation, and the influence of proportional compensation is limited to the initial response.
2. The proportional and integral parameters for males are greater than for females because females have higher heart rates than males at the same load.

The remainder of this paper is organized as follows. Section 2 presents the research problem for this study. In Sect. 3, the control law is designed directly from the exercise data of a subject. Section 4 presents the results of exercise experiments conducted using the designed control law. Finally, conclusions are presented in Section 5.

Problem statement

Heart rate can be increased by exercise, but its dynamic characteristics vary from individual to individual. Spörri, *et al.* have identified the dynamic characteristics from the command work rate to the heart rate as first-order or second-order systems[26]:

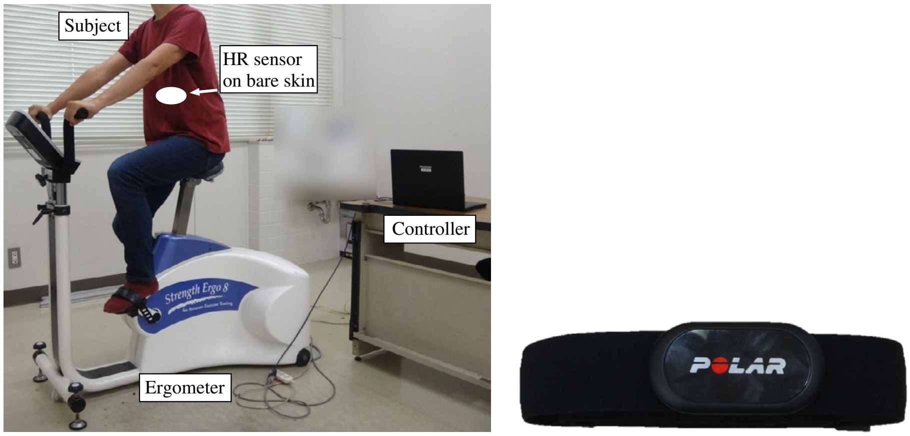
$$P_1(s) = \frac{k_1}{\tau_1 s + 1} \tag{1}$$

$$P_2(s) = \frac{k_2}{(\tau_{21}s + 1)(\tau_{22}s + 1)} \tag{2}$$

where k_i is the gain and τ_j are time constants.

Two issues must be resolved here. The first is the need to confirm whether the dynamic characteristics of heart rate can be expressed as such a linear system. Since the second is that transfer characteristics differ from individual to individual, in the case of model-based design, the transfer function needs to be identified for each individual. To confirm the first issue, preliminary experiments were conducted to understand the characteristics of the controlled process for each different subject. Figure 1a shows a scene from the experiment, and a heart rate sensor used in the experiment is shown in Figure 1b. All subjects who performed the preliminary experiment were healthy subjects, and their information is presented in Table 1. The conditions of the preliminary experiments are given in what follows:

- The sampling and control periods are 1 second.
- The subject pedals the ergometer at 50 [rpm].
- The subject exercise for 300 seconds at step-type work rates of 20 [W], 40 [W], 60 [W], 80 [W], 100 [W], and 120 [W], respectively, as shown in Figure 2.



(a) Subject, ergomete r and controller (b) Heart rate sensor

Figure 1. Schematic diagram of the experimental setup.

Subject	Gender	Age
A	Male	20s
B	Male	20s
C	Male	30s
D	Male	40s

Table 1. Subjects for the preliminary experiment.

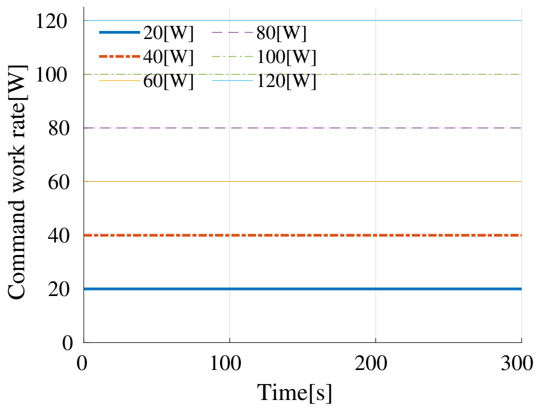


Figure 2. Command work rates for the preliminary experiment.

Since the ergometer used in the proposed system provides the subject with a command load independent of the pedal rotation speed, it is not necessary to maintain the rotation speed. However, in order to create the best possible experimental conditions, the subjects were asked to pedal at a constant speed. The control results for subject A are shown in Figure 3. After approximately 180 seconds, although the heart rate is not constant, the magnitude of the heart rate can be distinguished according to the load. When the steady state is defined as the period from 180 to 300 seconds from the start of the exercise time at each constant watt, the mean heart rate at the steady state for each subject is shown in Figure 4, where the steady-state average heart rates for subjects A, B, C, and D are indicated by "◯", "△", "▽", and "□", respectively. These experimental results show that the heart rate varies among subjects even when the same load is applied. The heart rate to load of the subjects varies not only with age but also within the same age group.

Figure 4 also illustrates the least-squares approximated straight line between watts and mean heart rate, and these results indicate that the relationship between load and heart rate is linear in each subject. These results are consistent with previous studies[36] showing that the relationship between load and heart rate is linear. Therefore, this study proposes a control method for heart rate based on linear theory. The second issue is solved not by a model-based approach but by the data-driven design method described in the next section.

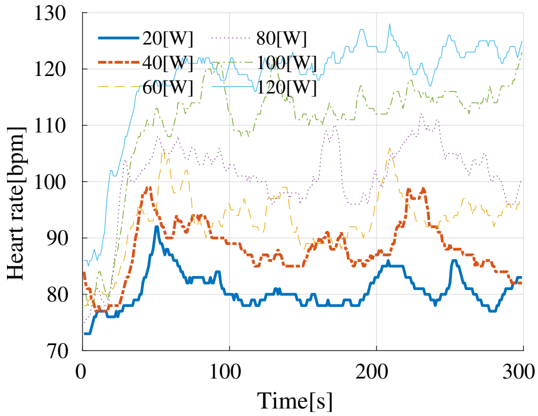


Figure 3. Experimental results of subject A at constant load.

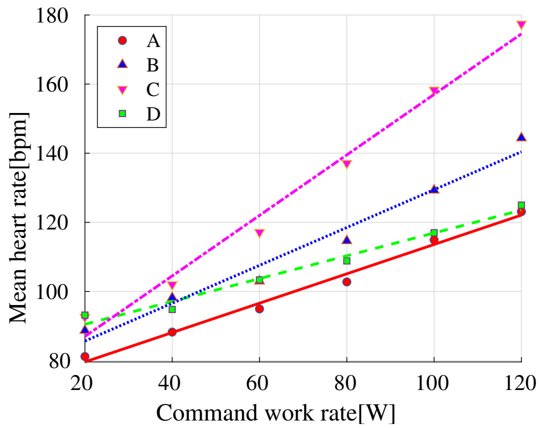


Figure 4. Relationship between work rate and steady-state heart rate.

Controller design

From the preliminary experiments, it is assumed that the dynamic characteristic from the command work rate $u(k)$ commanded to an ergometer to the heart rate $y(k)$ measured by a heart rate sensor is described by the following discrete-time linear time-invariant transfer function:

$$P(z^{-1}) = \frac{Y(z^{-1})}{U(z^{-1})}, \tag{3}$$

where $Y(z^{-1}) = \mathcal{Z}[y(k)]$ and $U(z^{-1}) = \mathcal{Z}[u(k)]$. $\mathcal{Z}[\cdot]$ denotes the Z-transform, and z^{-1} is the backward shift operator. As shown in the preliminary experiments, the transfer function $P(z^{-1})$ varies from subject to subject. Since identifying $P(z^{-1})$ for each subject is not only time consuming to implement, but also degrades control performance due to modeling errors, a control law for the unknown $P(z^{-1})$ is designed in this study.

The heart rate control system is implemented using a fixed-structured control law described as follows:

$$u(k) = C(z^{-1}, \boldsymbol{\theta})e(k) \tag{4}$$

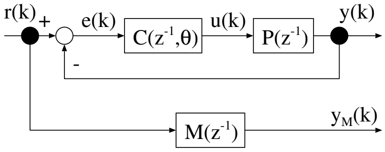


Figure 5. Block diagram of a model reference problem.

$$C(z^{-1},\boldsymbol{\theta}) = \boldsymbol{b}(z^{-1})^{\top}\boldsymbol{\theta}$$
$$e(k) = r(k) - y(k), \tag{5}$$

where $r(k)$ is the target heart rate that the measured heart rate should reach during the first 300 seconds of exercise. Also, $\boldsymbol{b}(z^{-1})$ and $\boldsymbol{\theta}$ are the vectors of controller structure and controller parameters, respectively. In this study, since the PI control law is used, $\boldsymbol{b}(z^{-1})$ and $\boldsymbol{\theta}$ are described as follows:

$$\boldsymbol{b}(z^{-1}) = \begin{bmatrix} 1 & \dfrac{1}{1-z^{-1}} \end{bmatrix}^{\top} \tag{6}$$

$$\boldsymbol{\theta} = [K_P \;\; K_I]^{\top}, \tag{7}$$

where K_P and K_I are the proportional and integral parameters, respectively, which are called PI parameters. The design of the PI parameters is important because it greatly affects control performance. In this study, in order to increase the heart rate along the reference trajectory set by the designer, the PI parameters are determined based on the model reference problem shown in Figure 5, where $M(z^{-1})$ is a reference model with adjustable heart rate increase, and $y_M(k)$ is a reference model output. Therefore, an objective function which is minimized with respect to the PI parameters is given as follows:

$$J_{MR}(\boldsymbol{\theta}) = \left\| \left(\frac{P(z^{-1})C(z^{-1},\boldsymbol{\theta})}{1+P(z^{-1})C(z^{-1},\boldsymbol{\theta})} - M(z^{-1}) \right) W(z^{-1}) \right\|_2^2, \tag{8}$$

where $W(z^{-1})$ is a filter. Since $P(z^{-1})$ is unknown, Equation (8) cannot be minimized as it is.

To determine the PI parameters without using model $P(z^{-1})$, consider the objective function Equation (9) instead of Equation (8).

$$\begin{aligned} J_{VR}^{N}(\boldsymbol{\theta}) &= \frac{1}{N}\sum_{k=1}^{N}(u_L(k) - C(z^{-1},\boldsymbol{\theta})\bar{e}_L(k))^2 \\ u_L(k) &= L(z^{-1})u(k) \\ \bar{e}_L(k) &= L(z^{-1})\bar{e}(k) \\ \bar{e}(k) &= \bar{r}(k) - y(k) \\ \bar{r}(k) &= \frac{1}{M(z^{-1})}y(k), \end{aligned} \tag{9}$$

where Equation (9) consists of N finite data. $\bar{r}(k)$ is a virtual reference input, and $L(z^{-1})$ is the filter designed to make Equation (9) match Equation (8). With the optimal controller $C^{*}(z^{-1})$, the closed-loop system and the reference model coincide, and thus the following equation hold:

$$\frac{P(z^{-1})C^{*}(z^{-1})}{1+P(z^{-1})C^{*}(z^{-1})} = M(z^{-1}). \tag{10}$$

Using the two norms of the discrete-time transfer function, Equation (8) becomes

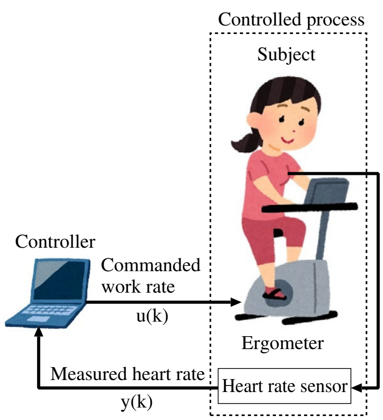


Figure 6. Schematic diagram of the heart rate control system ($u(k)$ is the command work rate, and $y(k)$ is the measured heart rate).

$$J_{MR}(\boldsymbol{\theta}) = \frac{1}{2\pi}\int_{-\pi}^{\pi}\frac{|P(e^{-j\omega})|^2|W(e^{-j\omega})|^2}{1+|P(e^{-j\omega})C(e^{-j\omega},\boldsymbol{\theta})|^2}\frac{|C(e^{-j\omega},\boldsymbol{\theta})-C^*(e^{-j\omega})|^2}{1+|P(e^{-j\omega})C^*(e^{-j\omega})|^2}d\omega. \tag{11}$$

When $N\to\infty$, Equation (9) becomes

$$J_{VR}^N(\boldsymbol{\theta}) \to J_{VR}(\boldsymbol{\theta}) = E[(u_L(k)-C(z^{-1},\boldsymbol{\theta})\bar{e}_L(k))^2]. \tag{12}$$

Using the Parseval's theorem, the above equation is rewritten as follows:

$$J_{VR}(\boldsymbol{\theta}) = \frac{1}{2\pi}\int_{-\pi}^{\pi}|P(e^{-j\omega})|^2|C(e^{-j\omega},\boldsymbol{\theta})-C^*(e^{-j\omega})|^2|1-M(e^{-j\omega})|^2\frac{|L(e^{-j\omega})|^2}{|M(e^{-j\omega})|^2}\Phi_u d\omega, \tag{13}$$

where Φ_u is the spectral density of $u(k)$. From Equation (10), since $1-M(z^{-1}) = \frac{1}{1+P(z^{-1})C^*(z^{-1})}$, $\boldsymbol{\theta}$, which minimizes Equation (9), minimizes Equation (8) when the number of data N is sufficiently large and the filter $L(z^{-1})$ satisfies the following equation[30]:

$$\begin{aligned} |L(e^{-j\omega})|^2 &= |1-M(e^{-j\omega})|^2|M(e^{-j\omega})|^2|W(e^{-j\omega})|^2\frac{1}{\Phi_u} \\ &\forall\omega\in[-\pi;\pi]. \end{aligned} \tag{14}$$

Since Equation (9) is rewritten as follows:

$$\begin{aligned} J_{VR}^N(\boldsymbol{\theta}) &= \frac{1}{N}\sum_{k=1}^{N}(u_L(k)-\psi_L(k)^\top\boldsymbol{\theta})^2 \\ \psi_L(k) &= \boldsymbol{b}(z^{-1})\bar{e}_L(k), \end{aligned} \tag{15}$$

the PI parameters that optimize Equation (15) are calculated as follows:

$$\hat{\boldsymbol{\theta}} = \left[\sum_{k=1}^{N}\psi_L(k)\psi_L(k)^\top\right]^{-1}\sum_{k=1}^{N}\psi_L(k)u_L(k). \tag{16}$$

With this design, the optimal PI parameters are obtained directly from a subject's exercise data.

#	Gender	Age	K_P^{tuned}	K_I^{tuned}	$J_{eval}^{initial}$	J_{eval}^{tuned}	J_{eval}^{diff}	$J_{eval}^{improved}$ [%]
1	Male	20s	0.272	0.0334	7.68	4.39	3.29	42.9
2	Male	20s	0.0922	0.0369	9.97	3.98	5.99	60.1
3	Female	40s	0.259	0.0210	3.63	3.62	0.0140	0.385
4	Female	50s	1.19	0.0126	9.13	3.73	5.40	59.2
5	Female	40s	0.877	0.0180	3.63	1.68	1.96	53.8
6	Female	50s	0.910	0.0278	4.66	1.80	2.86	61.5
7	Male	40s	1.75	0.0569	11.7	2.94	8.78	74.9
8	Male	50s	2.10	0.0421	9.56	2.23	7.33	76.7
9	Male	40s	1.14	0.0212	4.11	3.16	0.950	23.1
10	Male	30s	0.968	0.0356	4.64	3.87	0.764	16.5
11	Male	30s	0.860	0.0301	6.95	4.03	2.93	42.1
12	Female	30s	0.408	0.0214	3.23	3.83	−0.608	−18.8
13	Male	30s	2.01	0.0237	8.54	5.07	3.46	40.6
14	Female	20s	0.384	0.0215	2.24	3.11	−0.873	−39.0
15	Male	40s	1.02	0.0434	9.78	3.31	6.47	66.1
Average	–	–	–	–	6.63	3.38	3.25	37.32

Table 2. Age, gender, tuned PI parameters, and evaluated values of heart rate control experiments before and after tuning.

Age	20s	30s	40s	50s
Target heart rate[bpm]	125	125	120	115

Table 3. Target heart rate[38].

Verification experiment

Model reference control experiments with data-driven design were conducted. Section 4.1 presents a control system in which subjects perform exercises that increase their heart rate. The subjects who participated in the experiment are presented in Section 4.2, and the protocol for the heart rate experimental control is shown in Section 4.3. Control results and discussion are presented in Section 4.5.

This experiment was conducted after obtaining approval from the ethics committee of Graduate School of Engineering, University of Hyogo in Japan. All methods performed were in accordance with relevant guidelines and regulations, and informed consent was obtained from all subjects.

Heart rate control system

A schematic diagram of the heart rate control system proposed in this study is shown in Figure 6. The system consists of a subject, a heart rate sensor, a controller, and an ergometer, details of which are as follows:

- Heart rate sensor : H10N (Polar, Kempele, Finland)[37]
- Controller : MATLAB (MathWorks, Massachusetts, USA) installed in a computer (OS:Windows10, CPU:Intel Core i7, RAM:32GB).
- Ergometer : StrengthErgo8 (Mitsubishi Electric Engineering, Nagoya, Japan)

The main functions of the heart rate control system are as follows:

- The sensor attached to a subject's chest measures the heart rate and is connected to the controller via Bluetooth.
- The controller determines the work rate to command the ergometer based on the subject's received heart rate measured by the sensor.
- The ergometer actually gives the subject the commanded work rate.

As shown in Figure 6, since the actual controlled process consists of a subject, the heart rate sensor, and the ergometer, it is necessary to design the control law in the controller based not only on the dynamic characteristics of the subject, but also on the dynamic characteristics from the commanded work rate to the measured heart rate.

Subjects

Subjects for the experiment were healthy volunteers who volunteered to take part in the experiment and were recruited on campus. The subjects were instructed about the experiment and only performed the experiment if they consented. Fifteen healthy subjects participated in the experiment, and their ages and genders are shown in Table 2.

Protocol of heart rate control

The procedure of the exercise experiment conducted in this study is as follows.

1. Measure resting heart rate.
2. Set the target heart rate $r(k)$[bpm] based on age as Table 3[38].
3. To find the optimal PI parameters for each individual, an initial exercise experiment is conducted with the initial PI parameters.
4. Set the reference model $M(z^{-1})$ and determine optimal PI parameters based on the initial experimental data in 3).
5. Rest for approximately 10 minutes until the heart rate returns to the resting heart rate.
6. Perform the exercise experiment using the PI parameters tuned from the exercise data for the same amount of time as the experiment using the initial PI parameters.

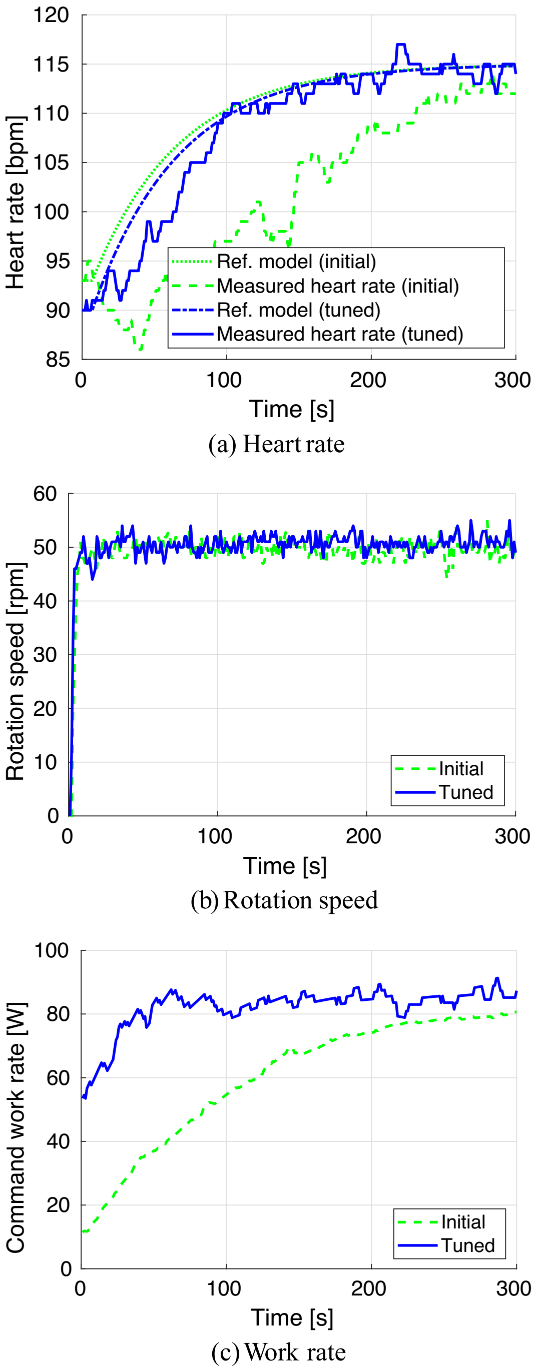
This exercise experiment procedure is performed for each subject.

Experimental conditions

In order to control the heart rate in a short period of time without strain, the duration of the exercise experiment is set to 5 minutes. The initial PI parameters are determined to be $K_P = 0.5$ and $K_I = 0.02$, respectively, after trial and error to reach the target values without excessive increase in heart rate due to 5 minutes of exercise. Since the ergometer used in this study provides the commanded work rate regardless of the pedal rotation speed, there is no need to set the rotation speed. The rotational speed to be maintained is set to 50 [rpm] by trial and error, as it is more desirable to have the same experimental conditions before and after tuning. The reference model that the control heart rate should follow is the following first-order plus dead-time system:

$$M(s) = \frac{1}{Ts+1}e^{-Ls}, \tag{17}$$

where the time constant T is set to 60 seconds to reach the target value in 5 minutes, and the dead time is 7 seconds, which is the time between the application of the load and the increase in heart rate in the initial



(a) Heart rate

(b) Rotation speed

(c) Work rate

Figure 7. Control results of subject #8 using the initial and tuned parameters.

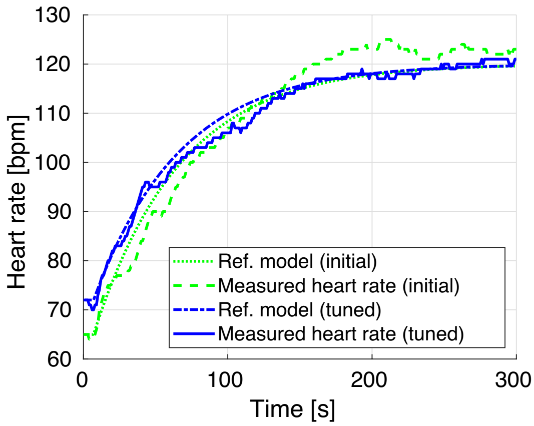
experimental data. The sampling period and control periods are 1 second, as in the preliminary experiment. Using the zero-order hold of the sampling period, $M(s)$ is converted to a discrete-time system, yielding $M(z)$.

Results and discussion

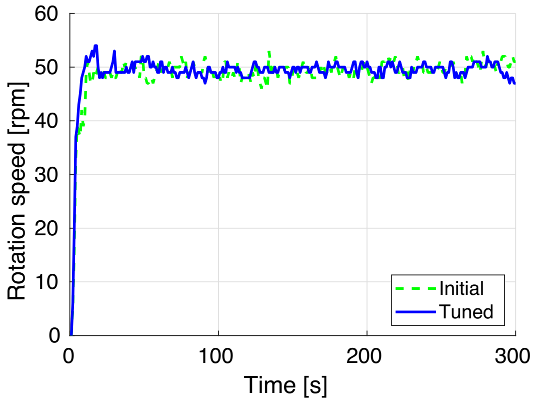
Control results before and after tuning

The control results are quantitatively evaluated by the following evaluation function:

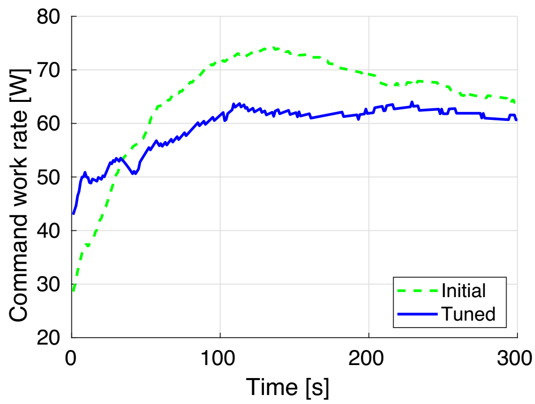
$$J_{eval} = \sqrt{\frac{1}{300}\sum_{k=1}^{300}(M(z^{-1})r(k) - y(k))^2}. \tag{18}$$



(a) Heart rate



(b) Rotation speed



(c) Work rate

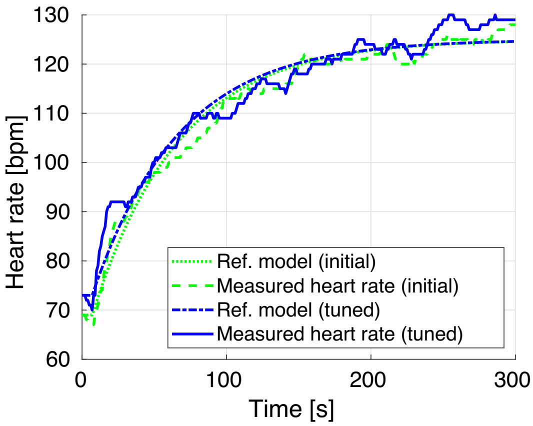
Figure 8. Control results of subject #5 using the initial and tuned parameters.

The evaluated values are summarized in Table 2, where the superscripts *init* and *tuned* refer to the use of initial parameters and tuned parameters, respectively. The table also shows the difference between the evaluated values before and after tuning, J_{eval}^{diff}, and the improvement rate, $J_{eval}^{improved}$:

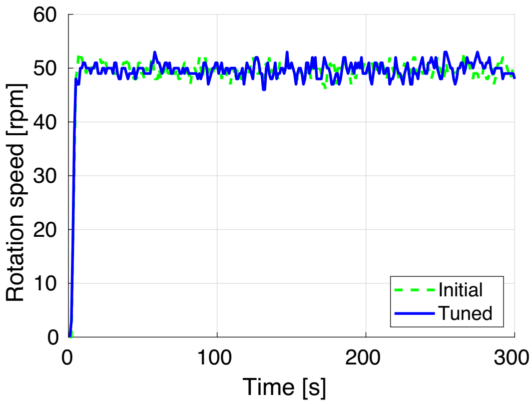
$$J_{eval}^{diff} = J_{eval}^{initial} - J_{eval}^{tuned} \tag{19}$$

$$J_{eval}^{improved} = \frac{J_{eval}^{initial} - J_{eval}^{tuned}}{J_{eval}^{initial}} \times 100. \tag{20}$$

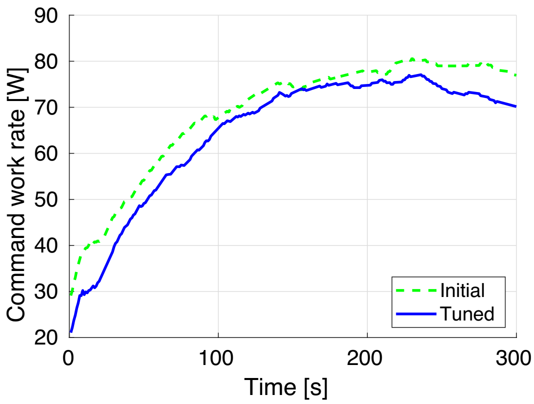
From the evaluation results, all except subjects #3, #12, and #14 show substantial improvement in control indices. Therefore, tuning effects can be broadly classified into improvement (all except #3,#12, and #14), maintenance



(a) Heart rate



(b) Rotation speed

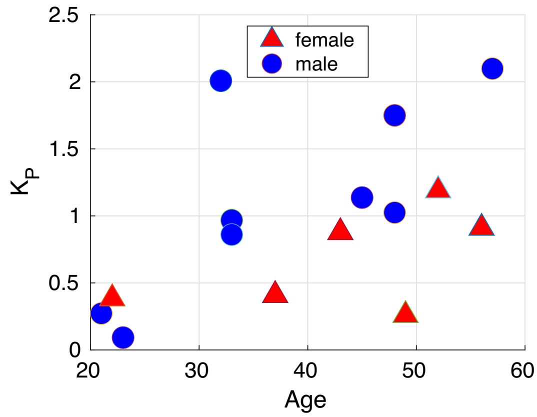


(c) Work rate

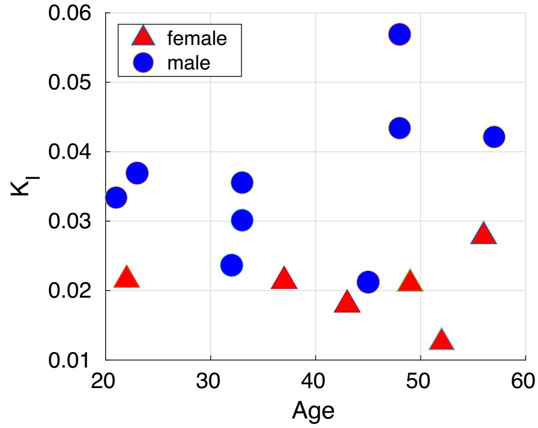
Figure 9. Control results of subject #14 using the initial and tuned parameters.

(#3), and deterioration (#12 and #14). In the comparison before and after tuning of subject #3, the proportional parameter is slightly smaller, but the integral parameter is almost unchanged, and the evaluated value is almost unchanged. Subjects #12 and #14, whose evaluated values deteriorated, showed large relative but not large absolute changes, indicating that control performance was generally maintained before and after tuning. What is common before and after tuning is that the proportional parameter changes slightly and the integral parameter is maintained. Although control performance varies greatly with PI parameters, the sensitivity to PI parameters is high for integral parameter, but not so high for proportional parameter.

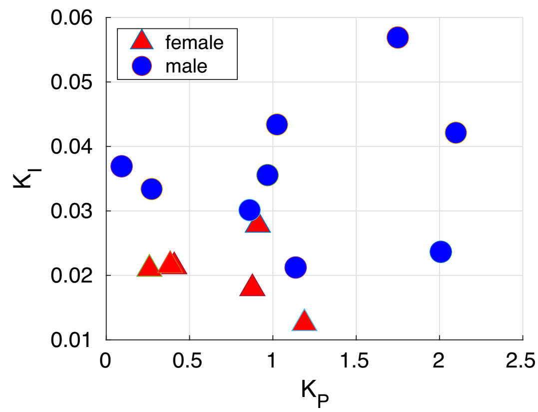
The time responses of subjects with the highest (#8), middle (#5), and lowest (#14) rates of improvement are shown in Figs. 7, 8, and 9, respectively, where (a), (b), and (c) are the heart rate, the pedal rotation speed, and commanded work rate, respectively. In the figures, the dashed green and solid blue lines show the results before and after tuning, respectively. Also, in Figure 7(a), Figure 8(a), and Figure 9(a), the dotted green and single-pointed blue lines are the reference model trajectories before and after tuning. From Figure 7(a), it can be



(a) Proportional parameter for age



(b) Integral parameter for age



(c) Integral parameter for proportional parameter

Figure 10. Relationship and distribution between tuned proportional and integral parameters and age.

seen at first glance that the control performance of #8 has been significantly improved. For #5, there is a slight performance improvement, and for #14, there is only a slight degradation before and after tuning.

As shown in Figure 7(b), Figure 8(b), and Figure 9(b), subjects exercised to maintain a pedal rotation speed of 50 [rpm] in all experiments. In this study, the controller is designed to follow the same reference model for subjects with different dynamic characteristics from commanded work rate to heart rate. Therefore, as shown in Figure 7(c), Figure 8(c), and Figure 9(c), by applying a different exercise load to each subject, it was confirmed that they all generally obtained the same heart rate response, despite their different dynamic characteristics.

In this study, fifteen healthy male and female subjects in their 20s to 50s were examined. Although the experimental results were limited to healthy subjects as in previous studies[21,25,26], the application of this method to subjects with diseases should be considered in the future.

Tuned PI parameters
The PI parameters tuned to follow the reference model Equation (17) using the initial experimental data for each subject with the initial parameters are summarized in Table 2. Figure 10 shows the tuned proportional and integral parameters for the subject's age, and furthermore, the relationship of the proportional and integral parameters for each subject. In Figure 10(a) and (b), the proportional and integral parameters for males are larger than those for females, suggesting that females tend to have higher heart rates at the same load. Figure 10(c) also shows that the proportional and integral parameters for females are smaller than those for males, indicating that females tend to have higher heart rates than males.

Conclusions
This paper has studied a design method for controlling the heart rate trajectory of a subject exercising on an ergometer. Since the dynamic characteristics from exercise load to heart rate vary from subject to subject, it is necessary to design a controller for each subject in order to obtain the response as designed. Since model-based design was used in conventional studies, modeling for each subject was very burdensome for the subject and was not suitable for optimal design of tracking characteristics. Therefore, in this study, we proposed a heart rate control system that provides work rate according to the subject using data-driven design, in which the controller is optimally designed directly from the subject's exercise data. In this study, the control system was developed using a linear data-driven design, confirming that the relationship between work rate and average heart rate is linear in the steady state. In the verification experiment of the proposed control system, the control results before and after tuning by fifteen volunteers were compared using the PI control law. The use of the PI parameters tuned from exercise data resulted in improved control performance in twelve of the fifteen subjects. The remaining three subjects generally maintained their absolute performance, although their relative performance deteriorated, confirming that the control system proposed in this study was effective for most subjects. This research has made it possible to provide optimal exercise for each subject with different characteristics. This is an outstanding achievement that distinguishes it from conventional exercise equipment, which could only provide uniform exercise, and is a very important achievement that will contribute to extending healthy life spans and improving the quality of medical care. Furthermore, after tuning PI parameters from exercise data, PI parameters tuned for female were often smaller than those for male. This provides a new objective indicator that female's heart rates tend to increase more than male's. Therefore, the control system proposed in this study not only safely increases the heart rate of each individual, but also has the potential to diagnose physical information.

In this study, the controller is limited to PI control, but design methods using more advanced controllers, such as PID control and higher-order control, should be considered in the future. Furthermore, future work is needed to address cases where dynamic characteristics change with exercise and nonlinear characteristics. In addition, the stability of the proposed method will be clarified in the future by referring to literature[39] where the dynamic characteristics of the system are not required.

The proposed system can be used to control the transient response of heart rate. However, the exercise time, the selection of initial PI parameters, and the design of the ideal transient response require further investigation from the medical and other perspectives.

Although the proposed heart rate control system is limited to healthy subjects, its effectiveness has been confirmed. Experimental results have confirmed that the heart rate can be controlled, and the system is expected to be used in cardiac rehabilitation and other situations where safe control of heart rate is required. We intend to apply this system to improve the prognosis of heart failure patients[23].

Data availability
The data are not publicly available due to policy restrictions imposed by the IRB at the University of Hyogo, Japan. However, the datasets can be provided by the corresponding author upon reasonable request and with permission from the IRB of the University of Hyogo, Japan.

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Author contributions

T.S. conceived the experiment, T.N., N.K., K.M., Y.K., and I.M. developed the control system, T.S., T.N., N.K., and S.K. conducted the experiments, H.M., H.U., I.M., S.K., and O.A. analyzed the results, T.S, S.K., and O.A. wrote the main manuscript text, and T.S and T.N prepared figures 1-8. All authors reviewed the manuscript.

Competing interests
The authors declare no competing interests.

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